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Blast Load Simulator Experiments for Computational Model Validation

Report 2

Frank D. Dallriva, Carol F. Johnson, James L. O'Daniel,
Andrew T. Barnes, and Cecil C. Dorrell

February 2017

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Frank D. Dallriva, Carol F. Johnson, James L. O'Daniel,
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Report 2 of a series

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Abstract

The Department of Defense needs the capability to accurately predict airblast environments produced by explosive detonations and their interaction with objects that create a complex geometry, such as buildings, bridges, dams, and others. First-principles computer codes are typically used to generate high-fidelity simulations of these explosive events and their effects. These codes are continuously improving, but still require validation against experimental data to establish confidence in the results produced by the simulations. This report describes a set of replicate experiments in which a small, non-responding aluminum box-type structure was installed and subjected to a simulated blast loading in a Blast Load Simulator (BLS) to provide pressure-time data at several locations on the surfaces of the structure. The BLS is a highly tunable compressed gas-driven, closed-end shock tube designed to simulate blast waveforms for explosive yields up to 20,000-lb of TNT equivalent at a peak reflected pressure up to 80 psi and a peak reflected impulse up to 1,100 psi-msec. Pressure and impulse waveforms are presented, and comparisons were made among the replicated experiments to evaluate repeatability. The uncertainty in the experimental pressures and impulses was evaluated by computing 95% confidence intervals on the results.

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Preface

This research was conducted for the Defense Threat Reduction Agency. The Technical Monitor was Dr. James L. O'Daniel.

The work was performed by the Structural Mechanics Branch (GSM) and the Research Group (GSR) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Bradford A. Steed was Chief, CEERD-GSM; James Davis was Chief, CEERD-GS; and Pamela G. Kinnebrew, CEERD-GZT, was the Technical Director for Survivability and Protective Structures. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Bartley P. Durst.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

1 Introduction

1.1 Background

The U.S. Department of Defense (DOD) needs the capability to accurately predict the airblast environment produced by explosive detonations and its interaction with objects that create a complex geometry, such as buildings, bridges, dams, and many others. First-principles computer codes are typically used to generate high-fidelity simulations of these explosive events and their effects. These codes have continued to improve over the last 20 years, but they still require validation against experimental data to establish confidence in the simulation results specific to their intended use.

One method for providing experimental data for computational model validation is to use a blast load simulator, such as a shock tube, to produce a simulated high-explosive blast environment. Generally, a shock tube can provide a repeatable blast environment at a significantly lower cost than conducting field experiments using explosives. Repeated experiments are often necessary to quantify the uncertainty in the experimental results for validating computational models.

1.2 Objective

The objective of this effort was to conduct a set of repeated experiments in the U.S. Army Engineer Research and Development Center (ERDC) Blast Load Simulator (BLS) to measure the pressure loading on a non-responding box-type structure located in the flow of the BLS simulated blast environment for use in evaluating computational models.

1.3 Approach

To meet the objective of this effort, a series of five replicate experiments were conducted in the BLS, using what is referred to as the 8x8 BLS configuration (Dallriva et al. 2016). The non-responding structure was installed in the BLS at a distance far enough downstream of driver and near the reflecting target plate to provide increased testing time undisturbed by the interface (contact surface) between the driver gases and the driven gases. Otherwise, the contact surface impinging on the structure would result in turbulent effects that significantly reduce experiment repeatability. Data from the five experiments were used to calculate 95% confidence

intervals on the results. The confidence intervals account for uncertainties associated with any small unknown or uncontrollable variations in experiment setup and conditions, and for any inherent random variability in the dynamic environment produced in this BLS experimental process.

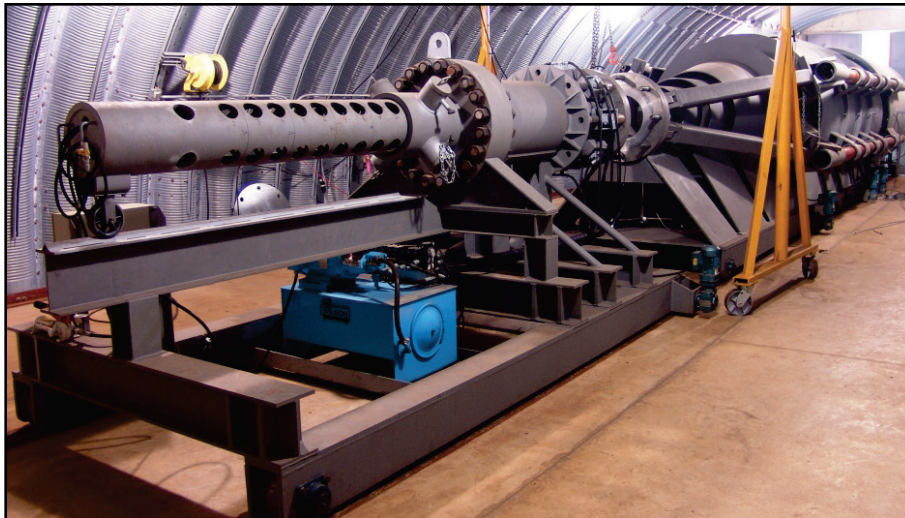
Pressure gauges were installed on the four sides and top of the structure and in a fixed steel plate (referred to as the calibration plate) at the end of the BLS, all for recording pressure vs. time at the gauge locations. Data plots are provided that include pressure-time and impulse-time histories, and a few comparison plots are provided for visual evaluation of test repeatability.

2 Experiment Descriptions

2.1 Blast load simulator

The ERDC BLS (Figure 1) is a highly tunable compressed gas-driven shock tube designed to simulate blast waveforms for explosive yields up to an equivalent of 20,000 lbs of TNT at a peak reflected pressure up to 80 psi and a peak reflected impulse up to 1,100 psi-msec (Johnson and Simmons 2008). The BLS has been used to evaluate the blast response of various structural test articles including windows, walls, and structural retrofit systems. It can simulate blast waveforms from very low pressures (1 to 2 psi) related to failures of conventional annealed glass and hollow concrete masonry unit walls to higher blast pressures required to evaluate the performance of protective construction methods.

Figure 1. ERDC Blast Load Simulator (BLS).



A recent addition to the BLS, referred to as the 8×8 configuration shown in Figure 2, includes a section to transition from the circular cross section that begins just downstream of the driver to a square cross section for testing 8-ft by 8-ft-square test articles, such as windows and walls. A detailed description of the BLS is provided in the first report of this experimental series (Dallriva et al. 2016).

Figure 2. View from exterior of 8x8 configuration.



2.2 Single-structure experiments in the BLS 8×8 configuration

Five replicate experiments were conducted in the BLS using the 8×8 configuration. An elevation drawing of this BLS configuration is shown in Figure 3 and a cross-section view from inside the GSA cascade section looking towards the target vessel showing the vertical location of the box structure relative to the BLS centerline is shown in Figure 4. The top of the box structure was located 19.5 inches below the horizontal centerline of the BLS. The centerline of the BLS is always defined with respect to the centerline of pressure vessel, regardless of asymmetry of the C2SQ section observable in Figure 3. Figure 5 shows a photograph inside the BLS viewing the structure and the steel calibration plate. The structure was mounted on an 8.5-in.-high steel pedestal welded to the bottom of the BLS. In each test the pressure vessel was pressurized, using air only, to a pressure of 1298 psi. A mechanical striker was used to initiate the pressure release through rupturing of the diaphragms. The diaphragms consisted of five layers that included one layer of 0.0155-in.-thick aluminum, one layer of 0.024-in.-thick aluminum, two layers of 0.0350-in.-thick steel, and one layer of 0.0345-in.-thick steel. Instrumentation included two pressure gauges mounted on the steel calibration plate and 25 pressure gauges mounted on the box structure. Figure 6 shows the gauge layout on the calibration plate. The box structure was 13 in. x 13 in. x 18 in. tall as shown in Figure 7. Figures 8 through 12 show the gauge layouts on the surfaces of the box structure. The two grayed-out gauge locations in Figure 8 denote locations not used for this series of testing. The front side of the structure in Figure 8

faces the pressure vessel and the rear side in Figure 9 faces the target plate. The left and right sides in Figures 11 and 12, respectively, are defined looking upstream from the target vessel towards to the pressure vessel.

Pressure measurements were made using either Kulite Model HKS-11-375 or XT-190 piezo-resistive pressure transducers. The data were transmitted over shielded mil-spec cable and recorded on a 16-bit Pacific Model 5810 Data Acquisition System. The acquisition system's sample rate was set for 1.0 μsec per point for the pressure measurements.

Figure 3. BLS 8x8 configuration with box structure.

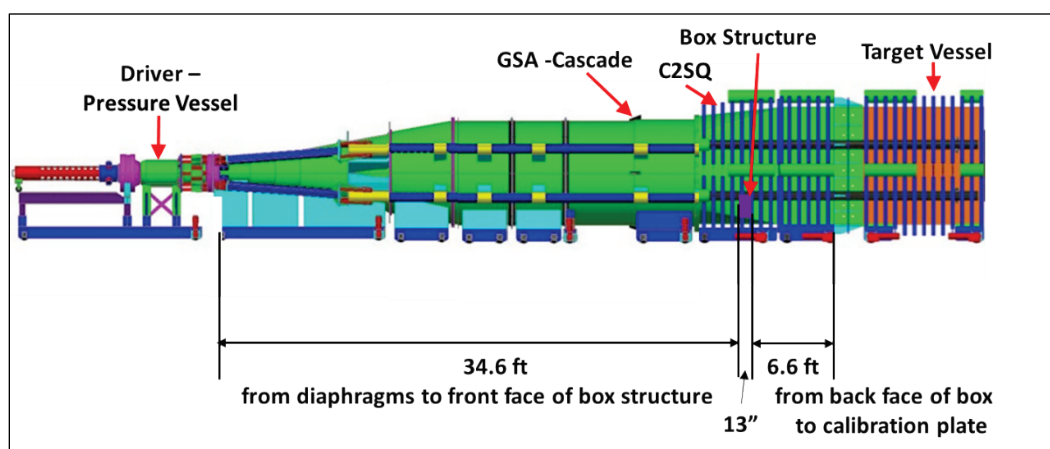


Figure 4. BLS cross section showing location of box structure.

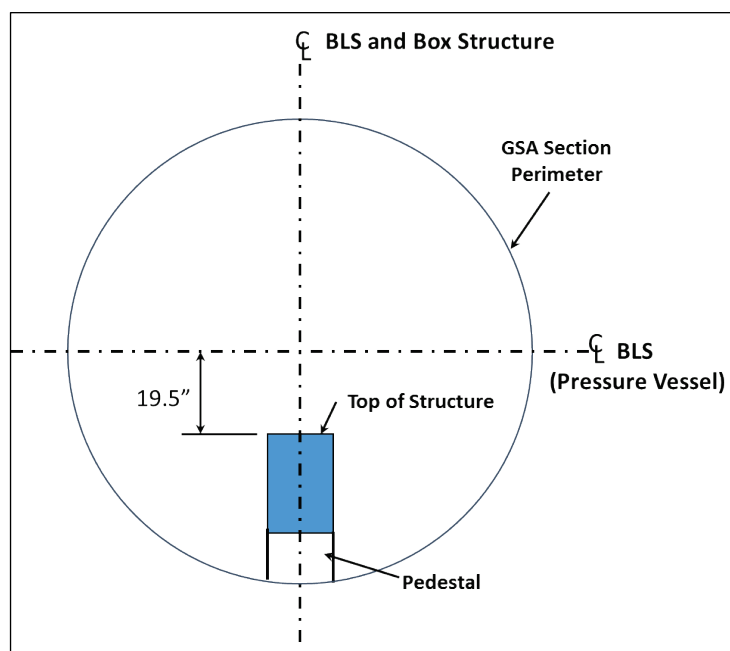


Figure 5. Photograph of box structure and calibration plate.

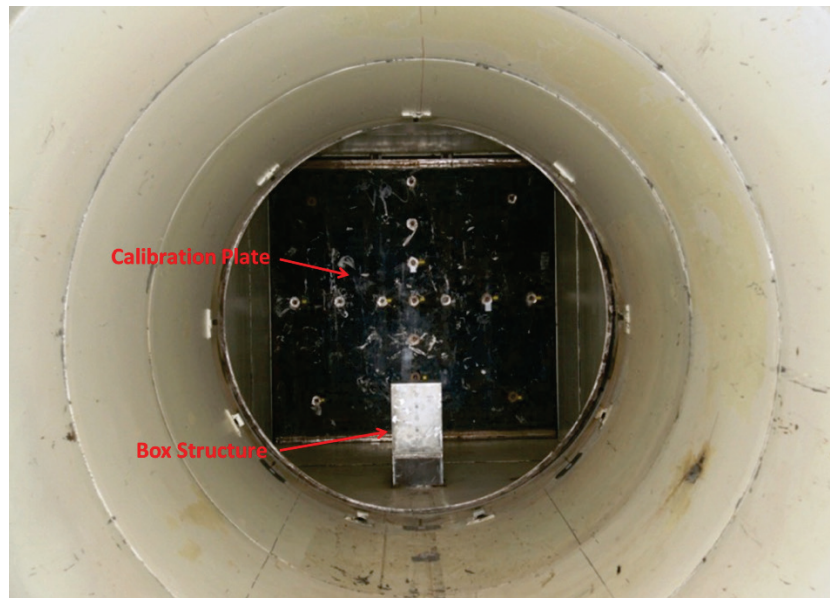


Figure 6. Gauge layout on calibration plate.

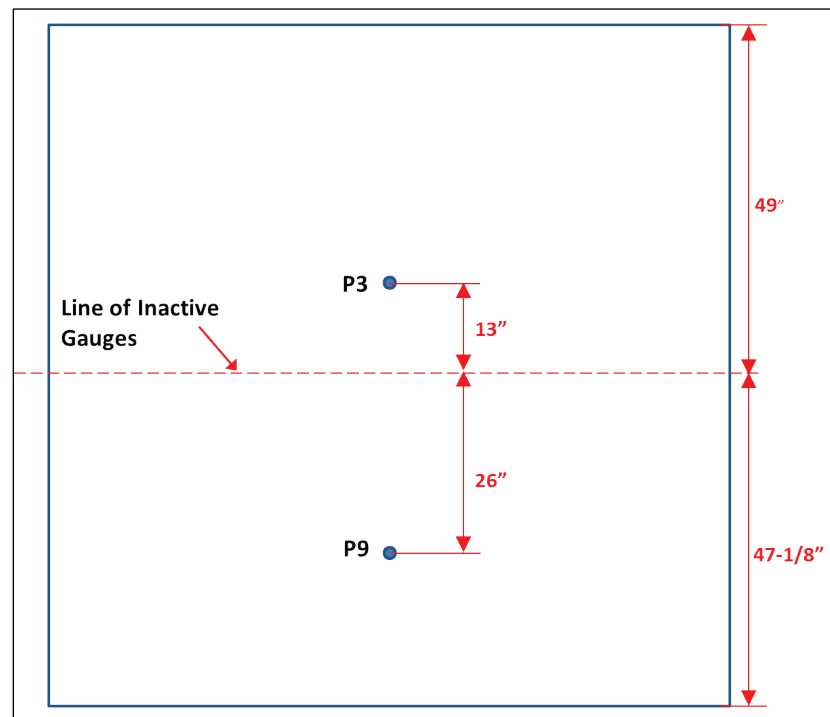


Figure 7. Box structure dimensions.

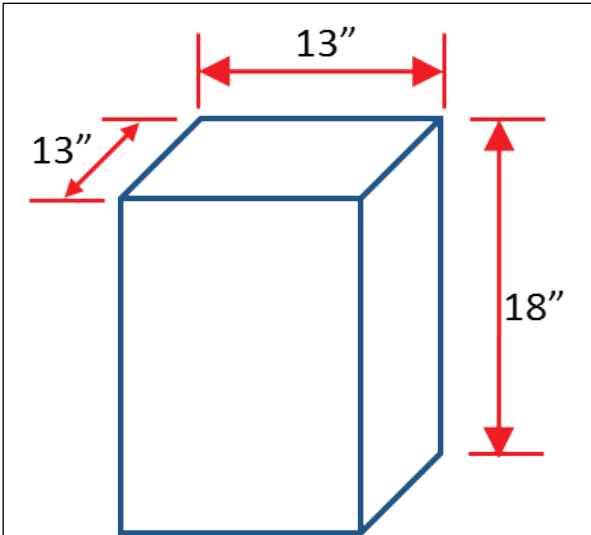


Figure 8. Gauge layout on front of structure.

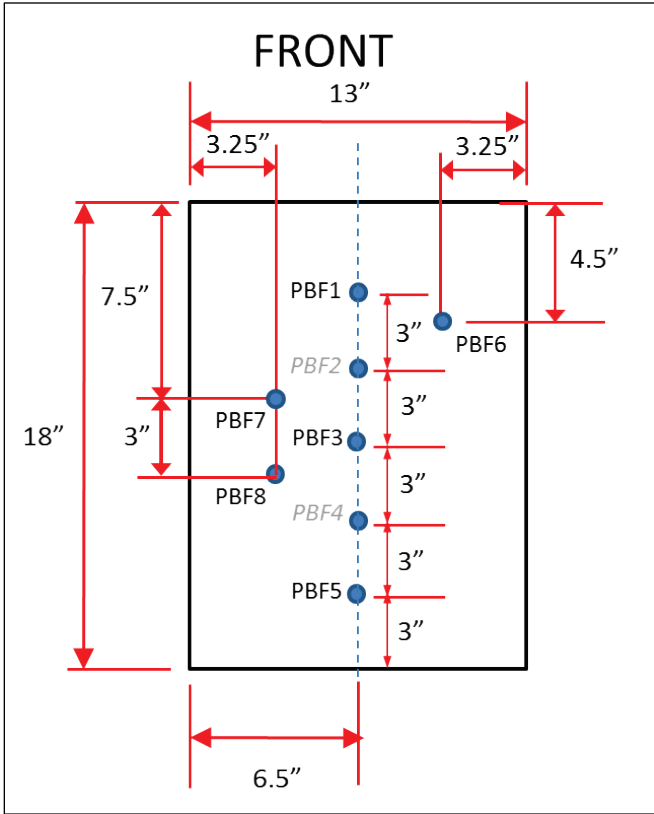


Figure 9. Gauge layout on back of structure.

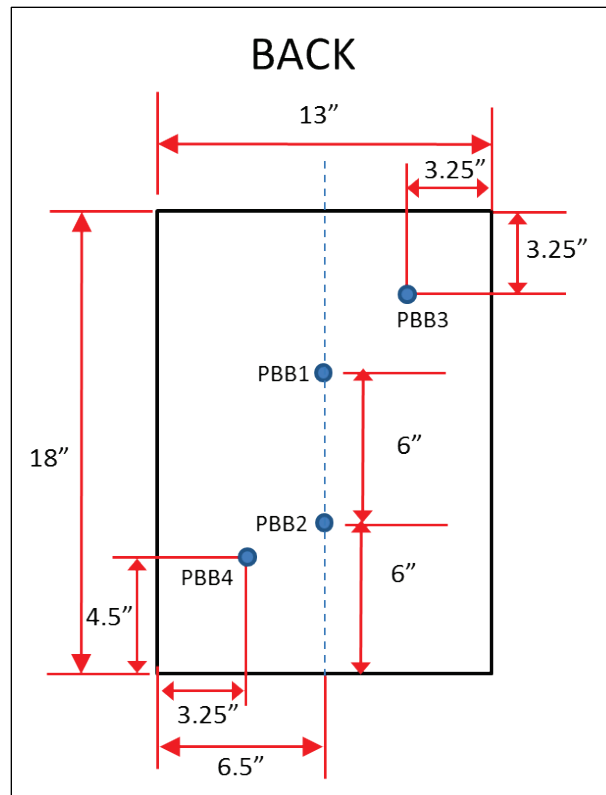


Figure 10. Gauge layout on top of structure.

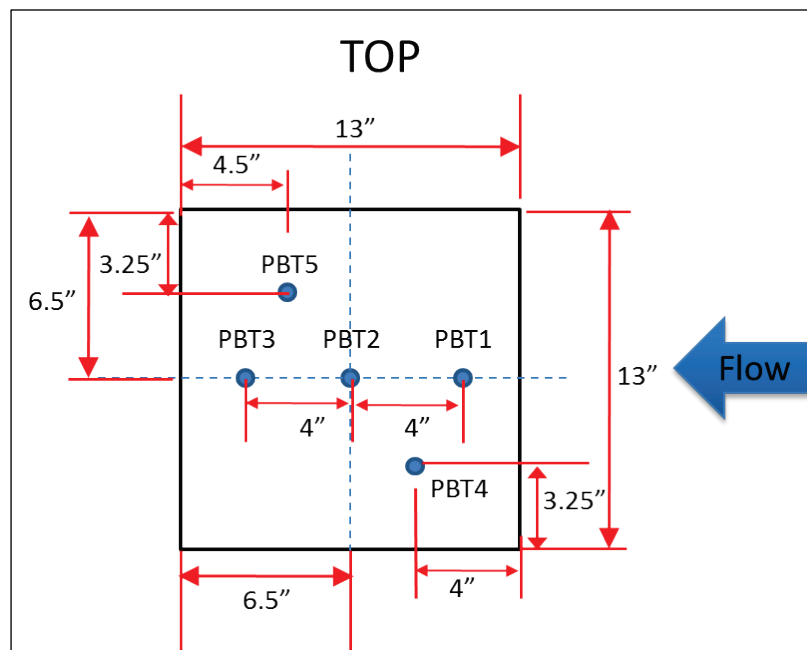


Figure 11. Gauge layout on left side of structure.

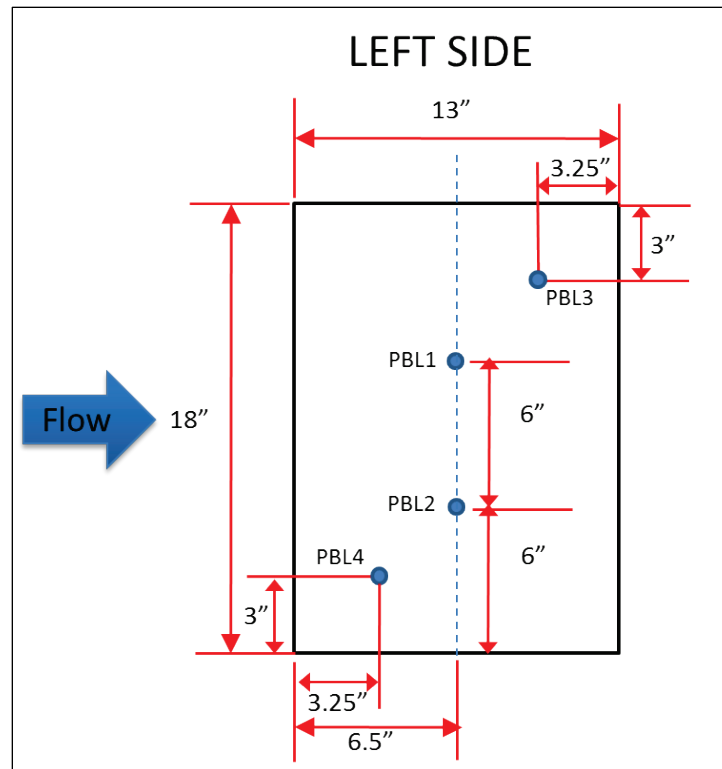
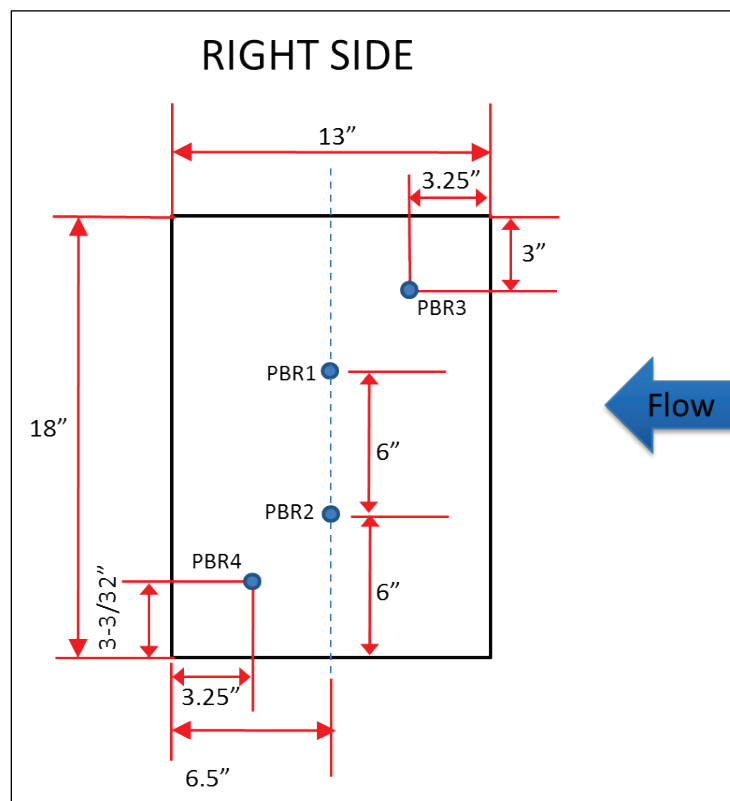


Figure 12. Gauge layout on right side of structure.



3 Experimental Results

3.1 Comparison of pressure waveforms

Reflected pressures on the target plate were very consistent among the five tests, demonstrating a high degree of repeatability. Figures 13 and 14 show comparisons of the pressure and impulse for all five tests from gauges CP3 and CP9 respectively, located on the calibration plate. A comparison of pressure waveforms recorded on the front, back and left sides of the structure are shown in Figures 15, 16, and 17, respectively, all of which show excellent repeatability among the replicate experiments.

Individual plots showing both pressure and impulse for all of the gauges from Experiments 1 through 5 are shown in Appendices A-1 through A-5 respectively.

Figure 13. Comparison of pressure records on calibration plate – Gauge CP3.

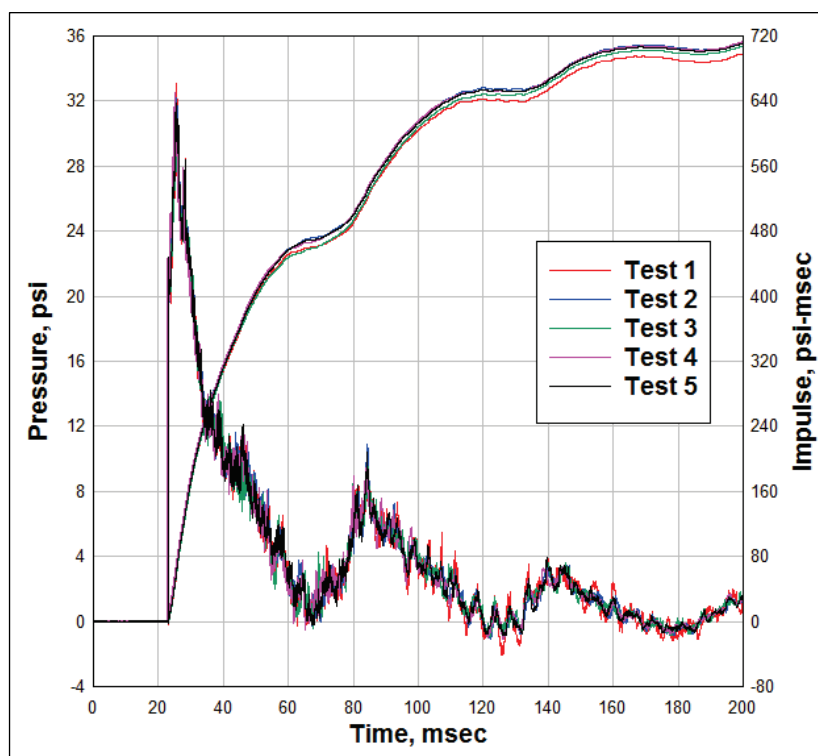


Figure 14. Comparison of pressure records on calibration plate – Gauge CP9.

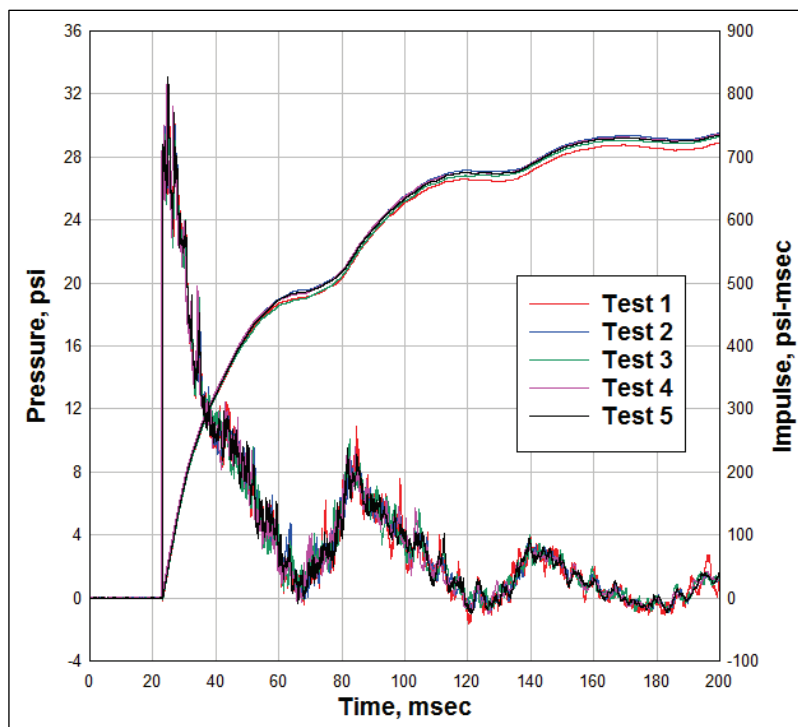


Figure 15. Comparison of pressure records on front of structure – Gauge PBF1.

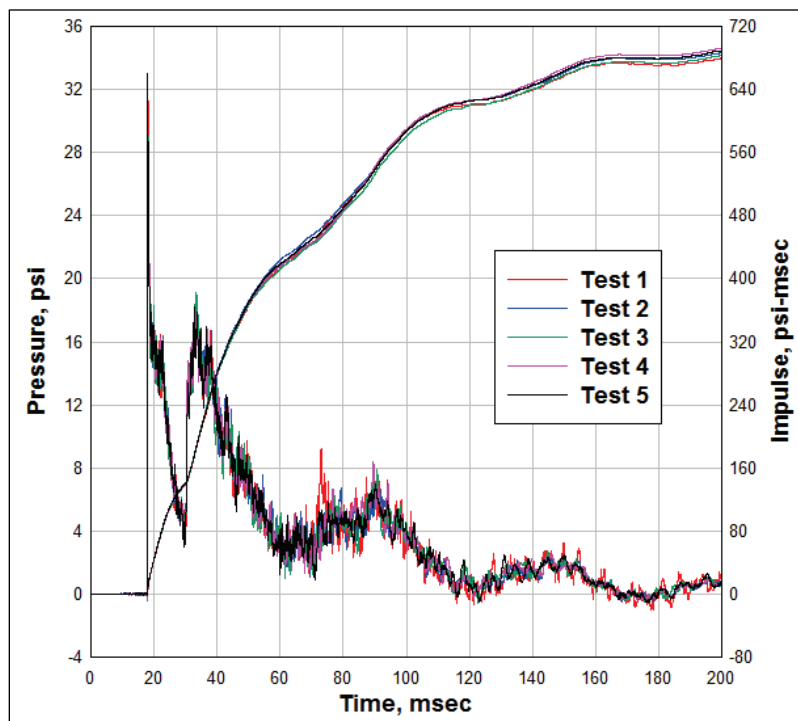


Figure 16. Comparison of pressure records on back of structure – Gauge PBB1.

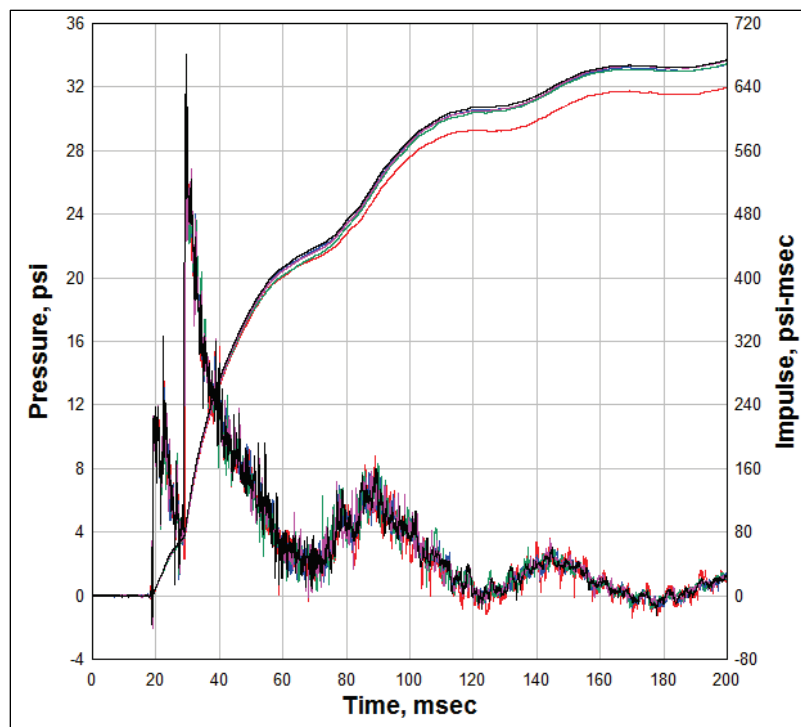
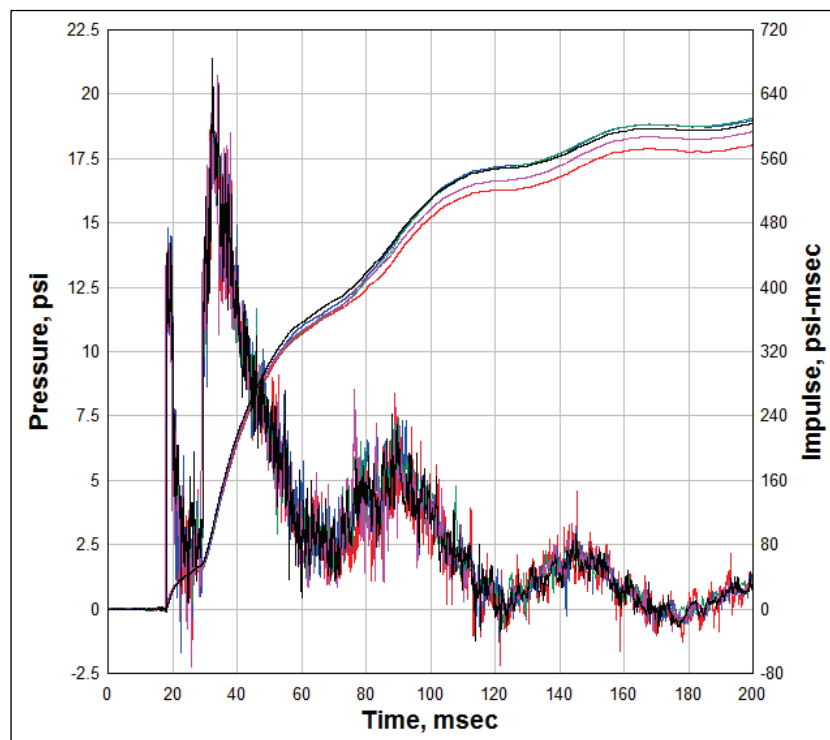


Figure 17. Comparison of pressure records on side of structure – Gauge PBL1.



3.2 Experiment uncertainty

The uncertainty in the experimental pressure and impulse was evaluated for the five replicate experiments for which, as closely as possible, the identical BLS setup was used from test to test. The analysis assumes that the data values constitute a sample population drawn from an underlying Gaussian parent population. Ninety-five percent confidence intervals were computed to provide the range within which one should expect the next data value to lie if an additional test were to be conducted.

The 95% confidence interval for a sample of N measurements of X drawn from a Gaussian distribution was based on the precision index, P , defined by the equation

$$P_X = tS_X$$

and the estimated 95% confidence interval is defined by

$$\bar{X} \pm P_X$$

where:

- \bar{X} = the sample mean of X
- S_X = the sample standard deviation
- t = the value from the t distribution with $N-1$ degrees of freedom corresponding to the 95% confidence limit

Figures 18 and 19 present the mean values and 95% confidence intervals computed for the initial peak pressure and for the total impulse at 120 ms respectively. Figures 13 through 17 demonstrate that a maximum impulse is not recorded during the time frame of interest for these experiments. Therefore, 120 ms was chosen as a representative time for impulse comparison consistent with the first report of this series and nearly corresponding to a local minimum in the pressure-time histories. As indicated by the confidence intervals and the waveform comparisons presented in Section 3.1, the data exhibited a very reasonable degree of repeatability among the five experiments

In Figure 19, gauge PBF6 is observed to consistently produce a significantly higher total impulse than the other front-face gauges. The 95% confidence interval on impulse for this gauge is $\pm 2.6\%$ of the mean

value demonstrating that this is a systematic not random difference. This behavior is not physically realistic for the face of the structure oriented 90 deg to a planar blast wave. For example, in Figure 8, PBF6 is shown to be closer to two free edges than gauges PBF3 and PBF5. Physically, the pressure closer to the free edges will be relieved sooner than in the center of the structure, resulting in a lower total impulse. The opposite behavior is shown in Figure 19. Although suspect, the results for PBF6 are included here to demonstrate the need for multiple gauge locations per face during the experimental phase of the study. If only a single gauge location on the front face was used, the non-physical results for PBF6 would not have been identified. It also emphasizes that the experimental data itself must be closely examined for any verification and validation effort. It is suspected that the sensitivity of gauge PBF6 drifted from its most recent calibration resulting in a systematic error. The gauge was submitted for recalibration to determine the source of the error. However, results are not available for this report.

Figure 18. Ninety-five percent confidence intervals on measured peak pressure.

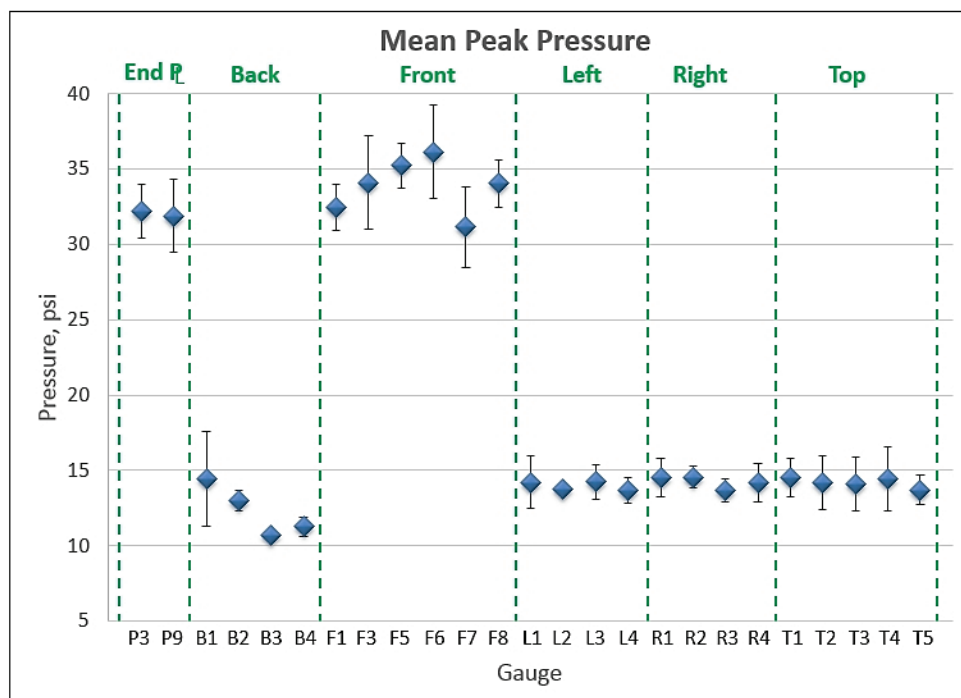
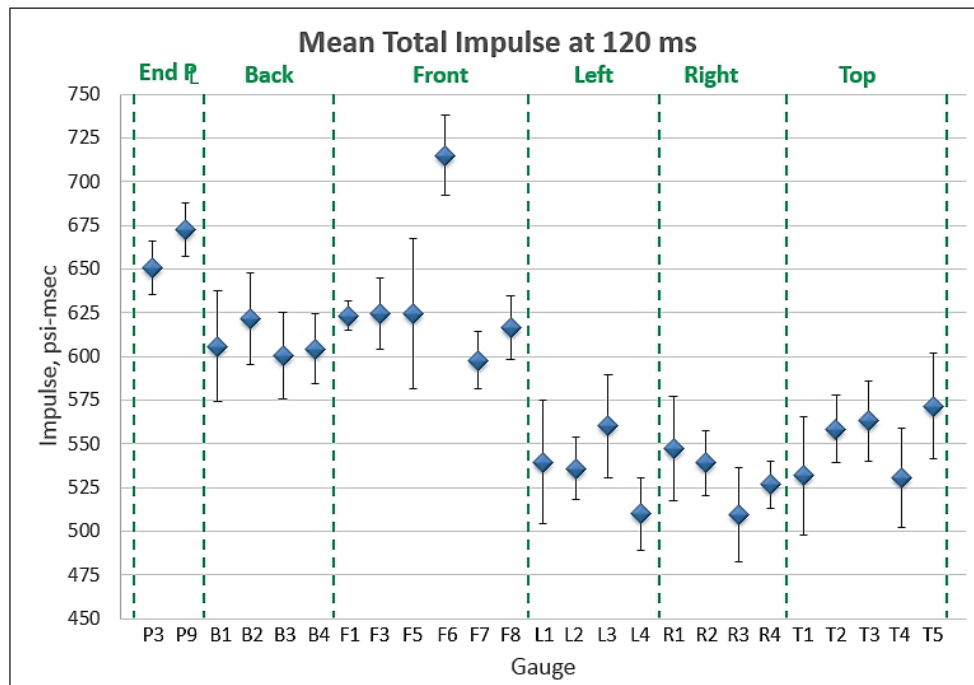


Figure 19. Ninety-five percent confidence intervals on measured total impulse at 120 ms.



4 Conclusions and Recommendations

Replicate experiments conducted in the BLS produced very repeatable pressure data on the surfaces of the box structure and on the calibration plate. All except one of the 95% confidence intervals for peak pressure were within ± 15 percent of the mean, and all of the total impulse confidence intervals were within ± 7 percent of the mean. Visual evaluation of overlaid waveforms for all five experiments at individual gauge locations showed excellent experiment repeatability. The pressure and impulse waveforms from the experiments combined with uncertainty information in the form of confidence intervals for peak pressure and impulse result in a data set that can be used to evaluate the accuracy of computational models.

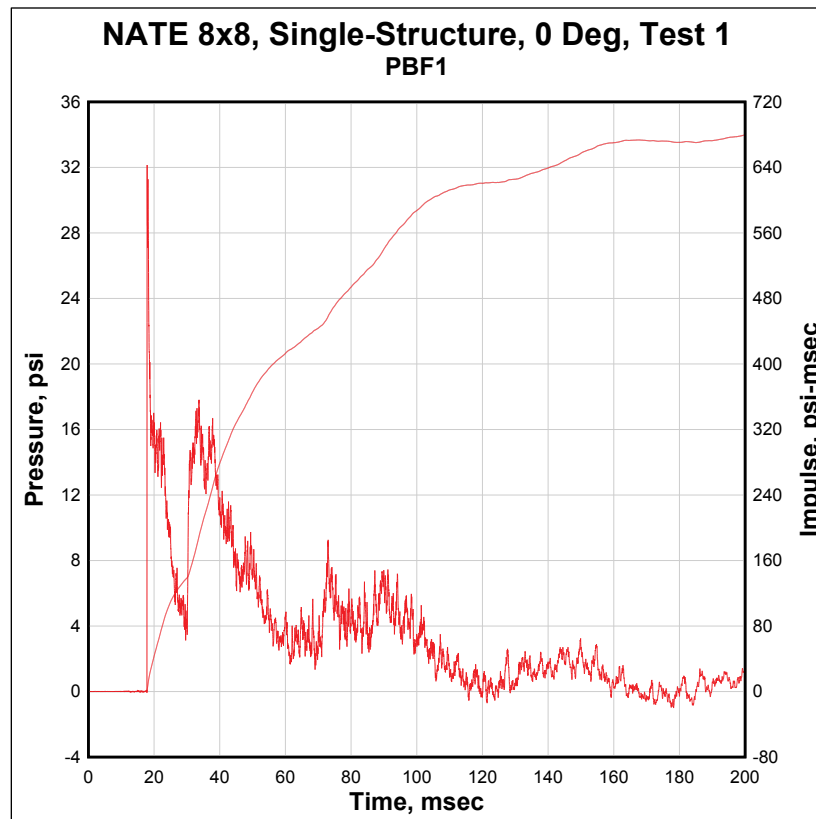
Future tests will be conducted for which an air gap will be introduced between the end of the 8x8 BLS test section and the steel calibration plate. This will be done to significantly reduce the magnitude of the pressure that reflects off of the calibration plate and back onto the box structure. Also, it will provide more time for the initial pressure to engulf the structure and decay prior to a reflection from the calibration plate impinging on the structure from behind.

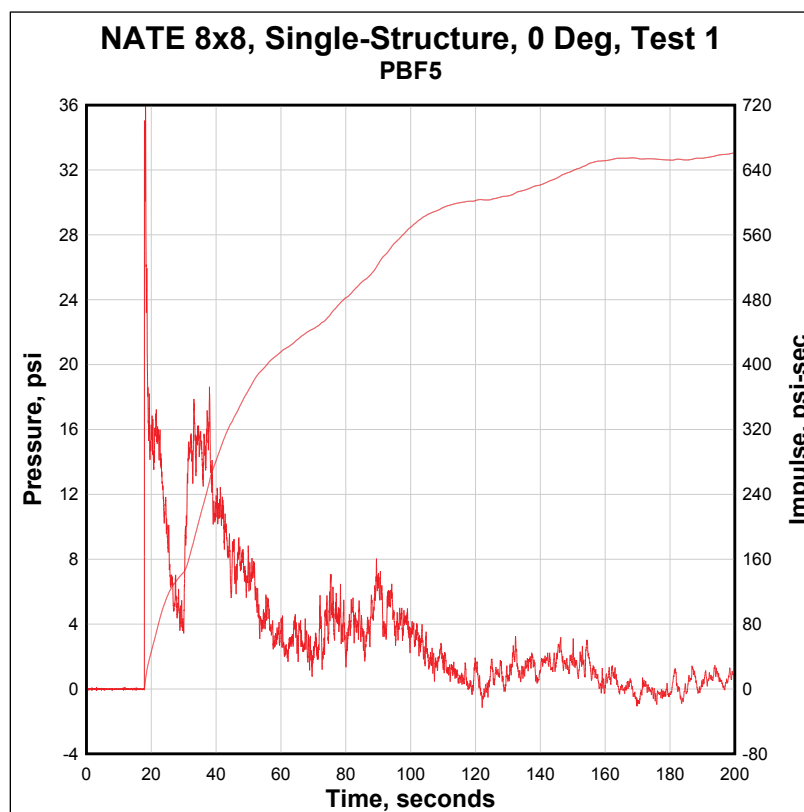
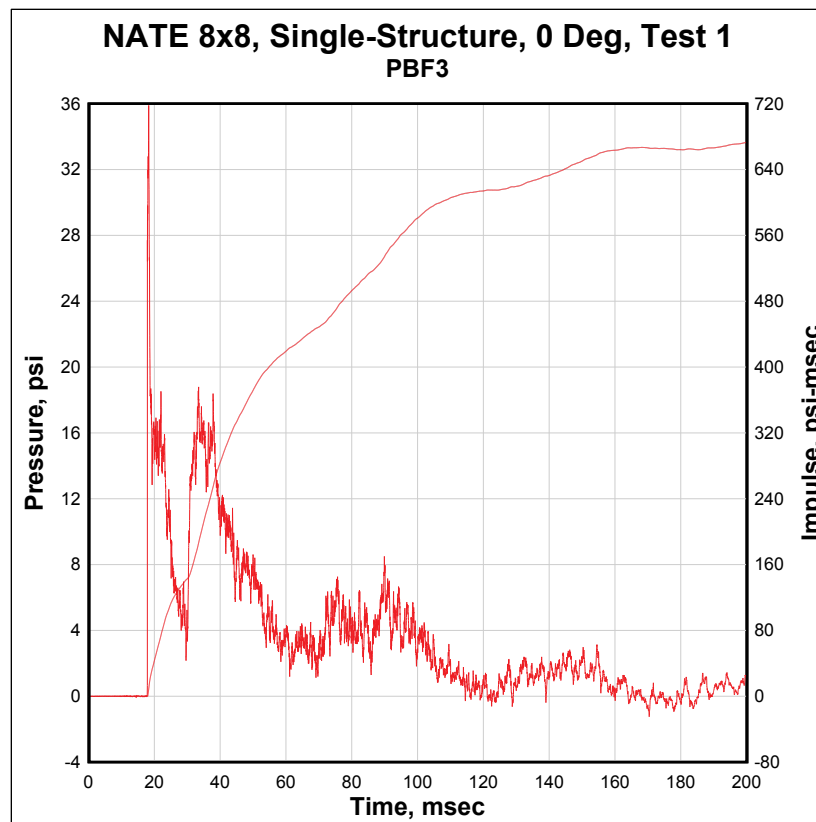
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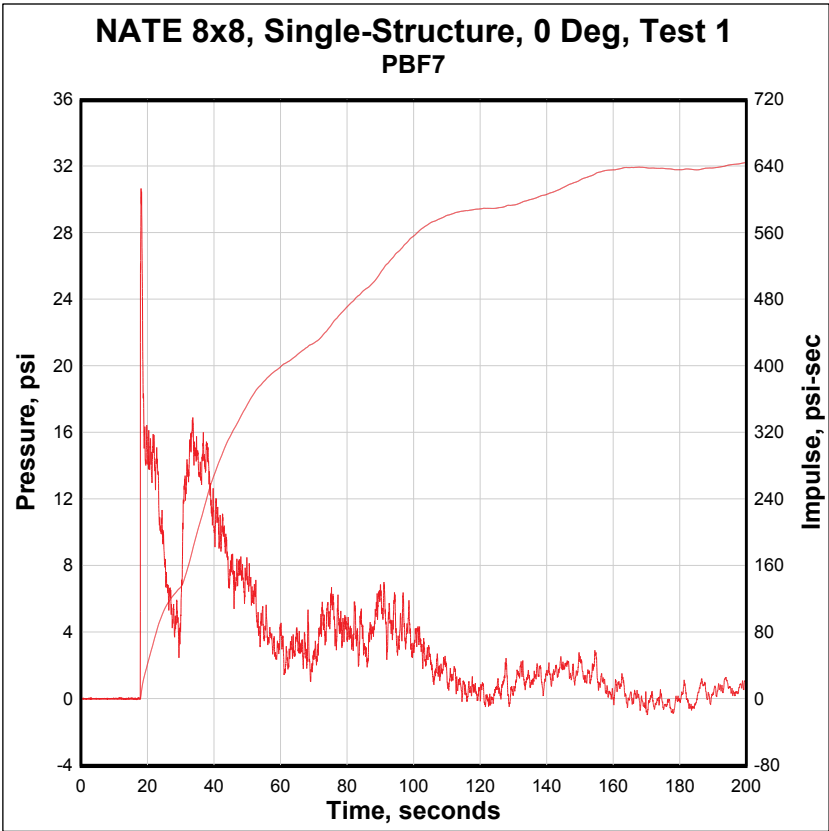
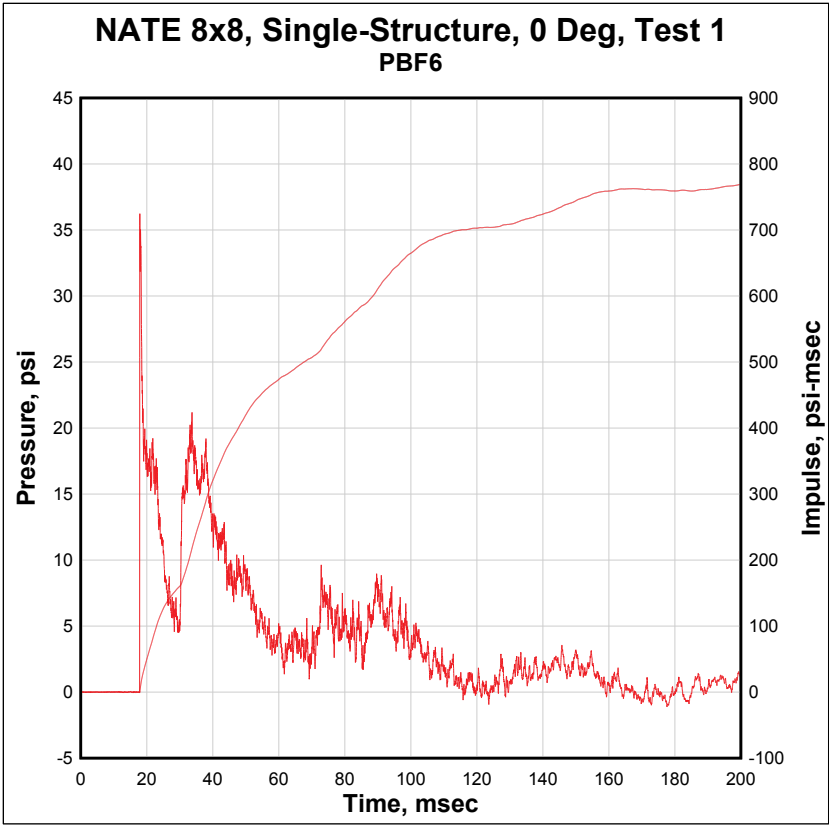
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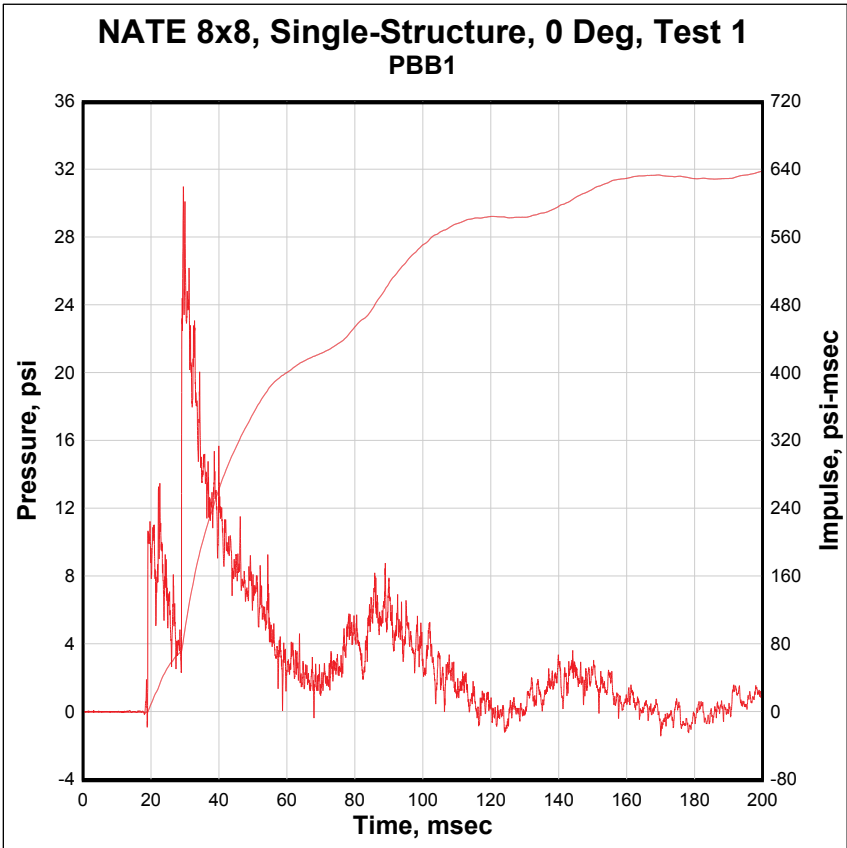
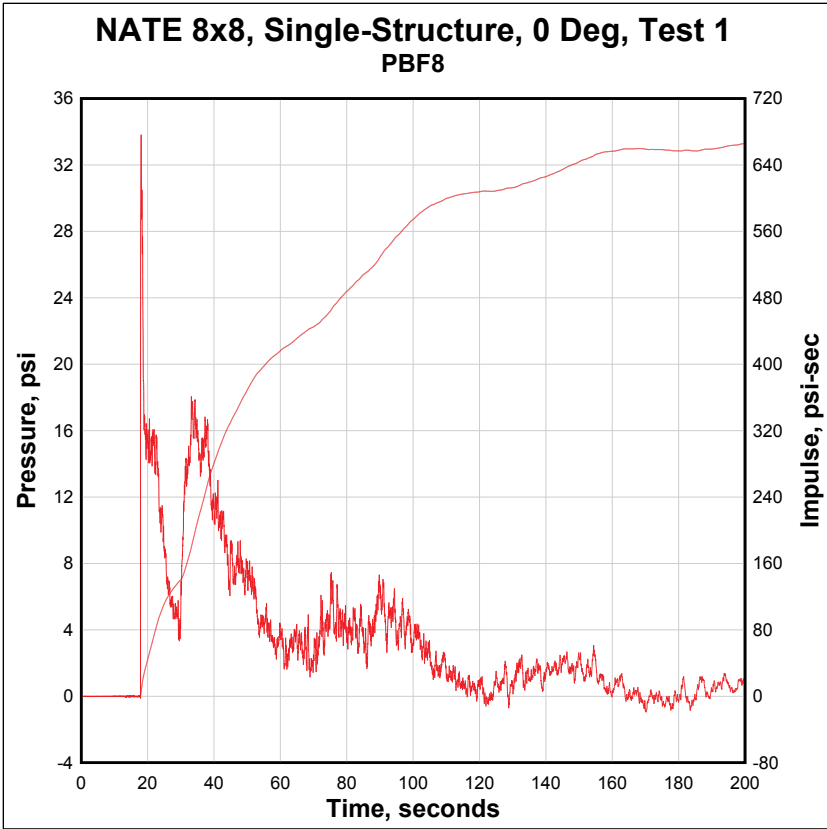
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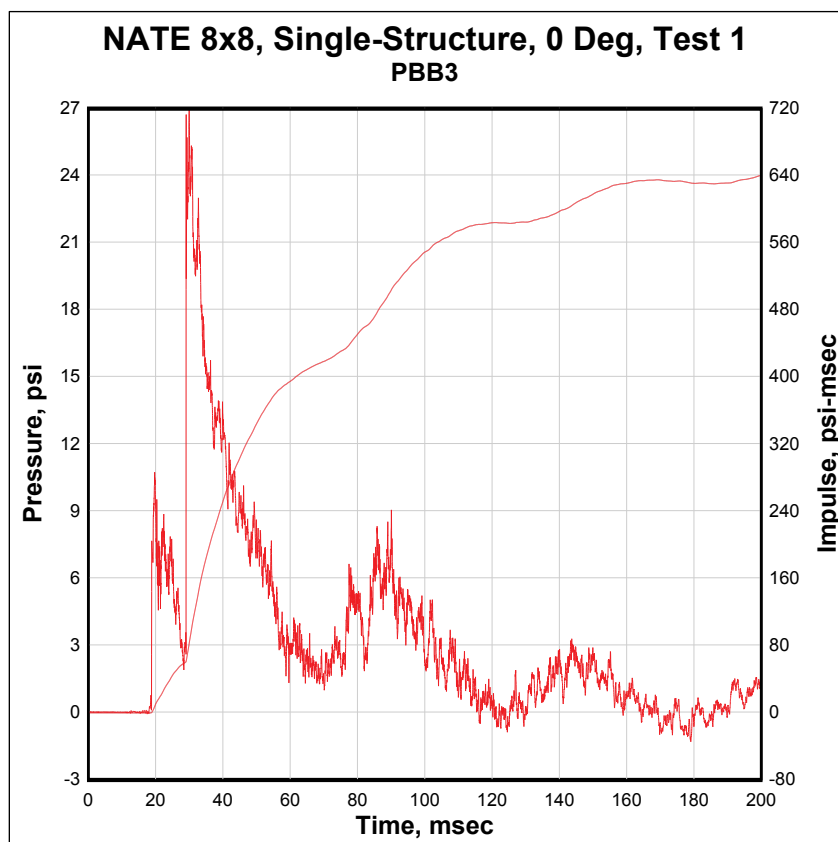
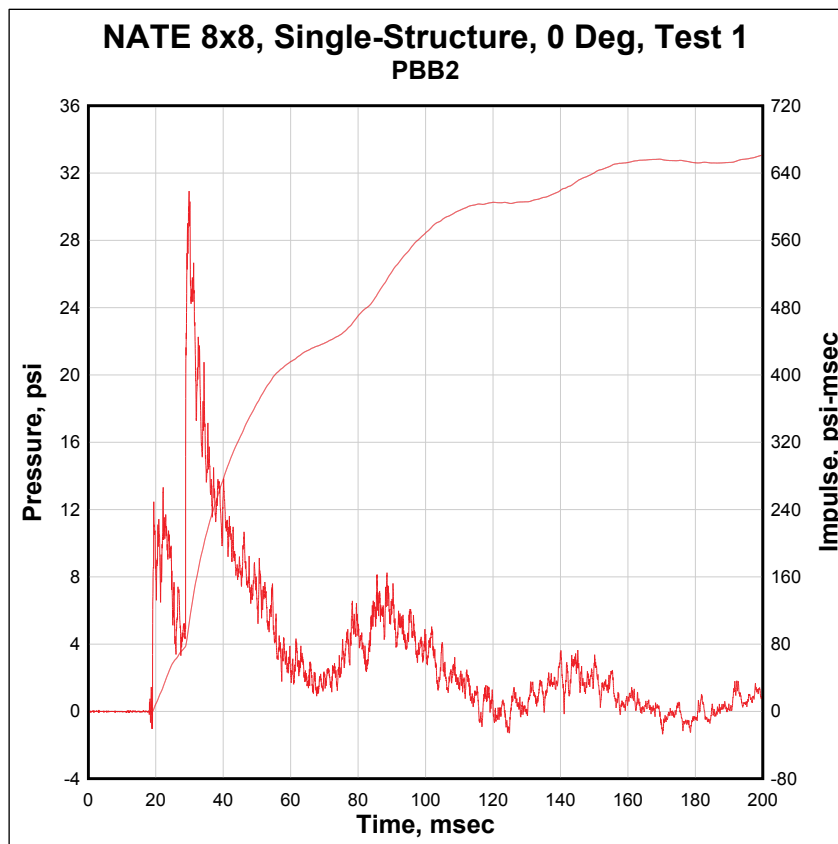
Appendix A: Pressure and Impulse Data from Test 1

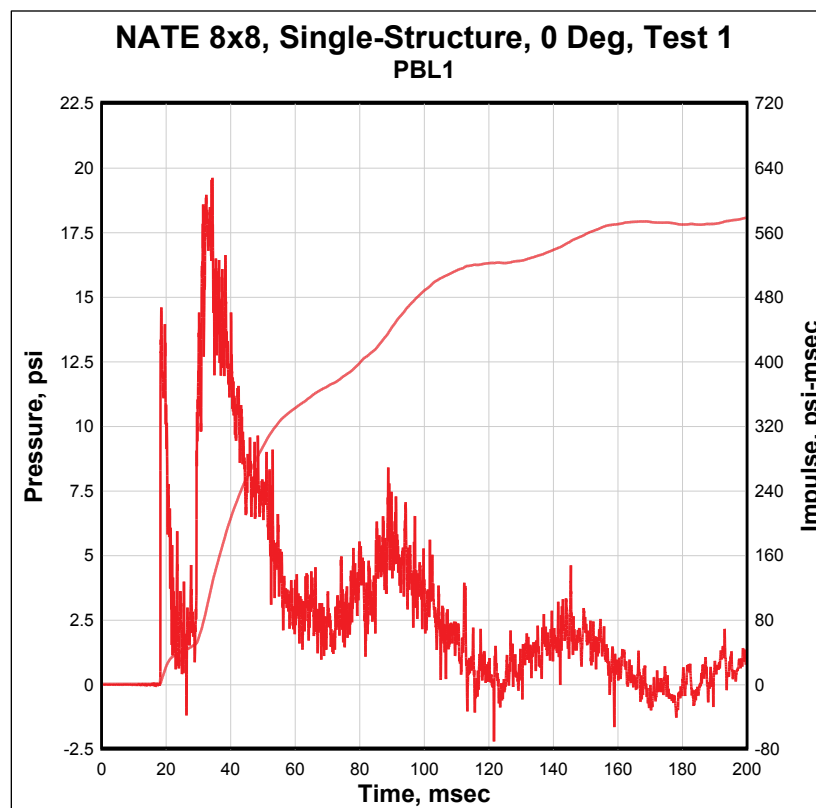
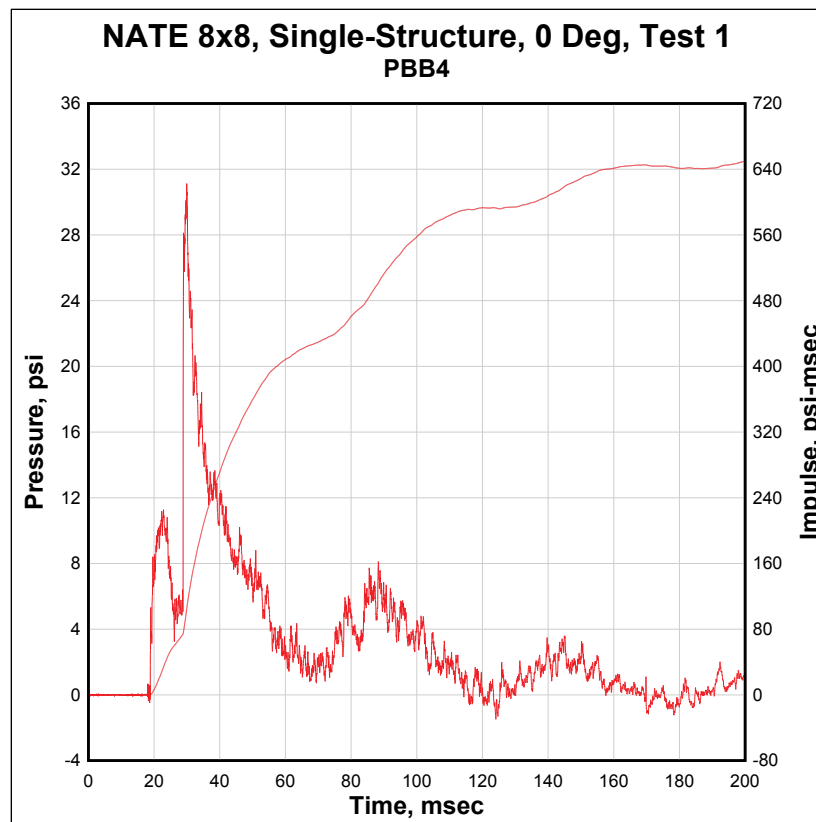


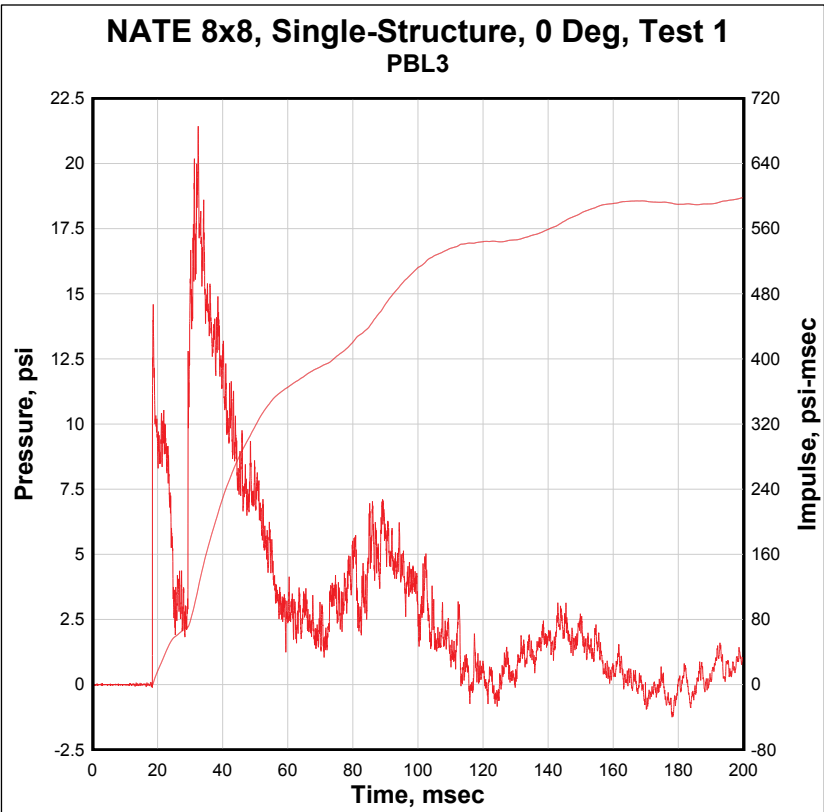
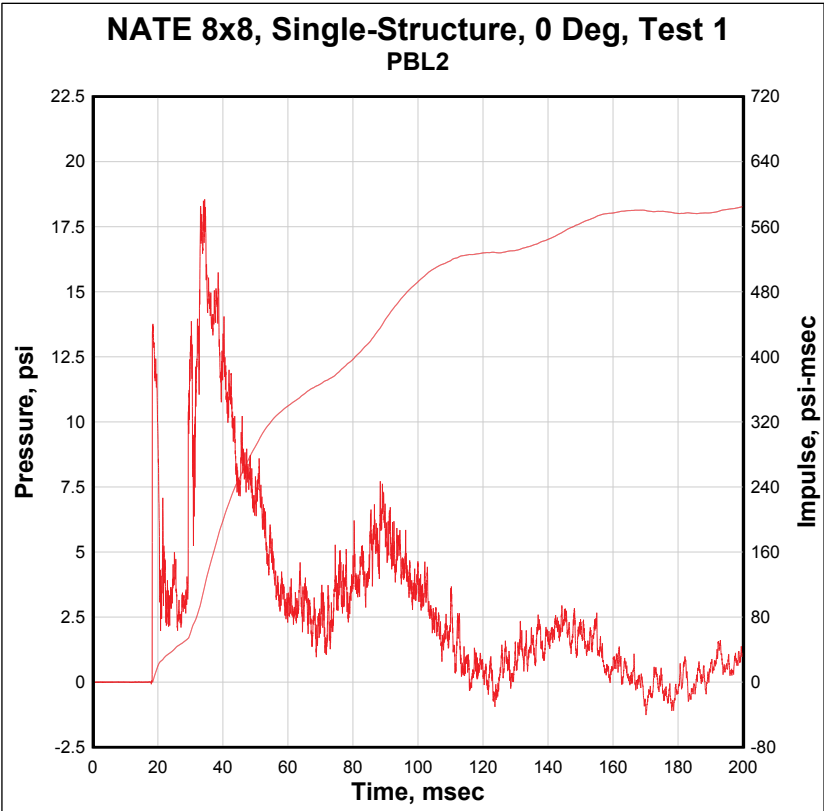


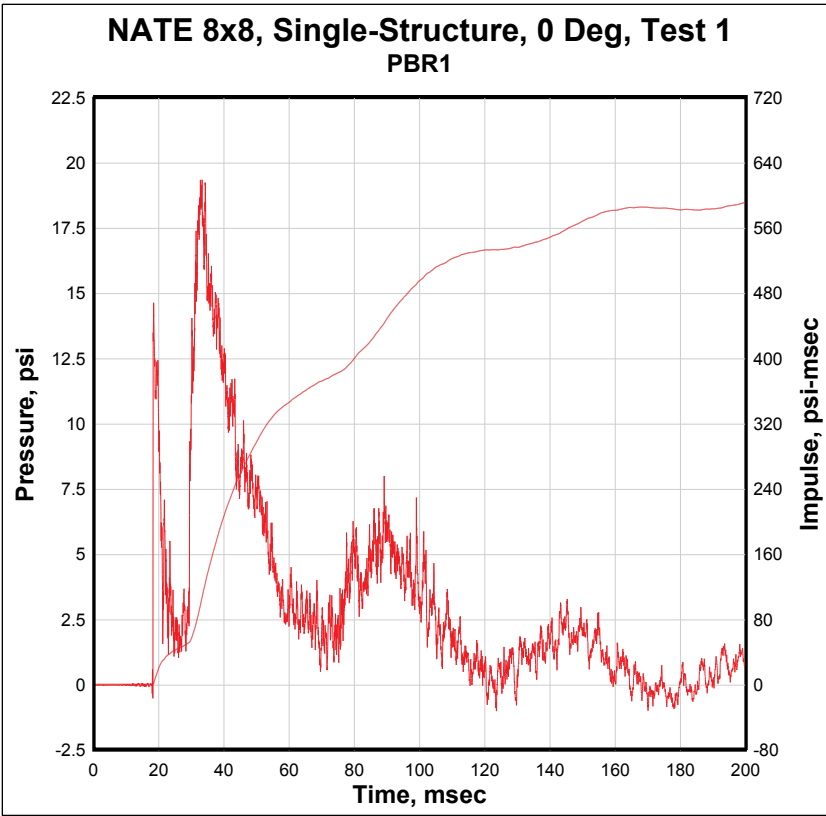
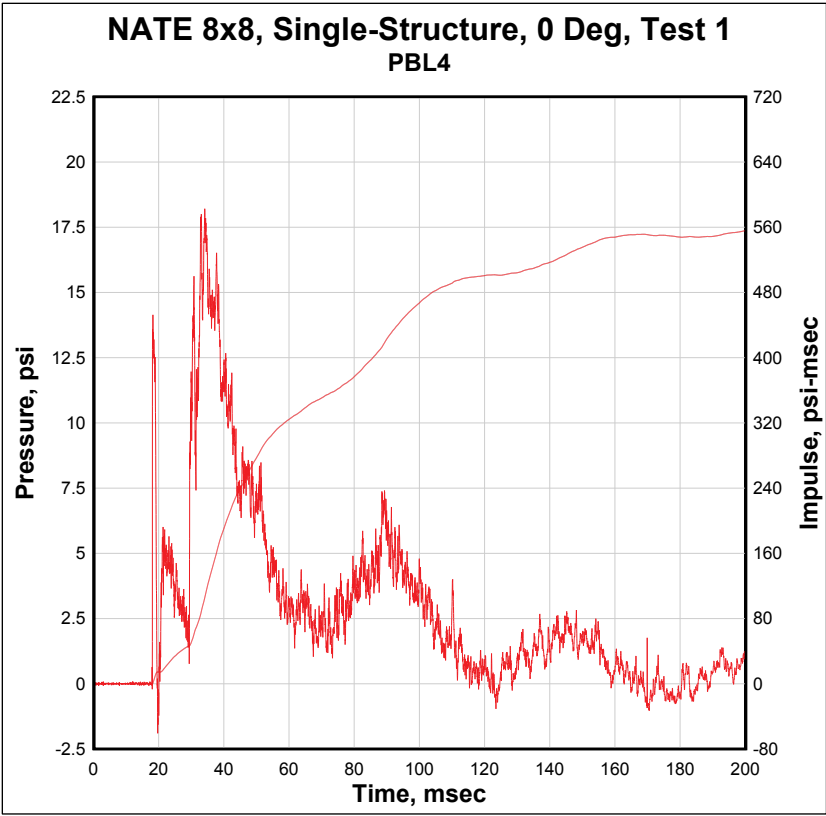


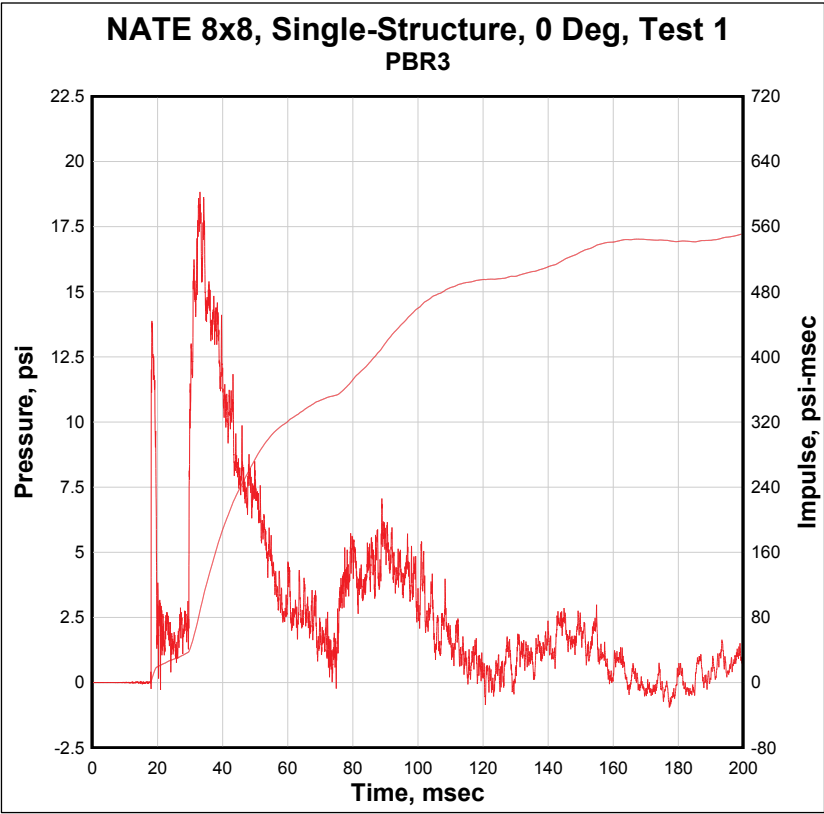
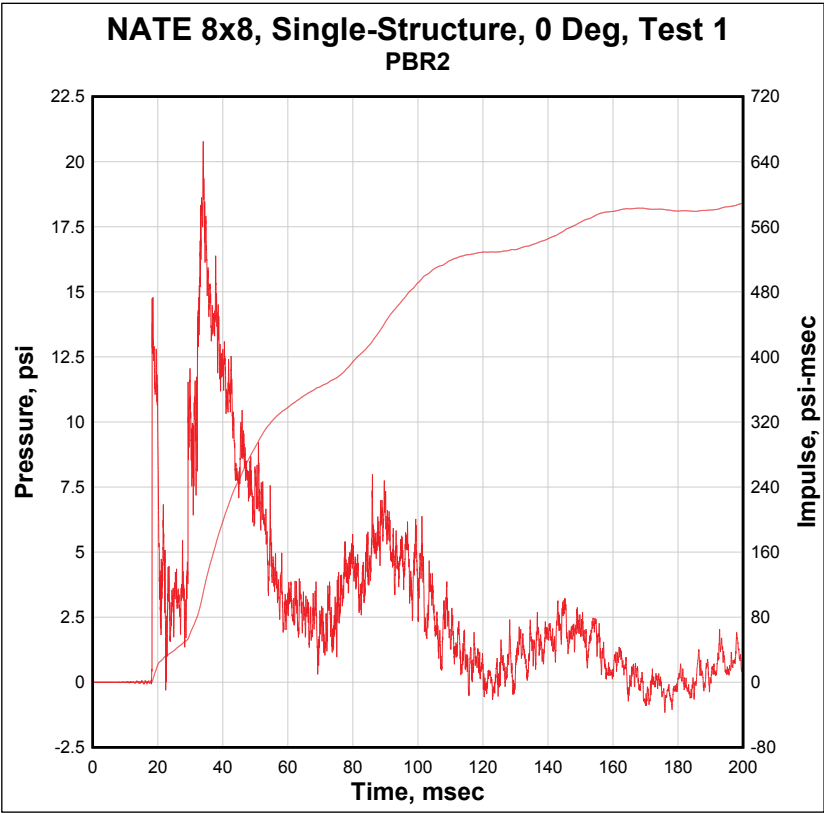


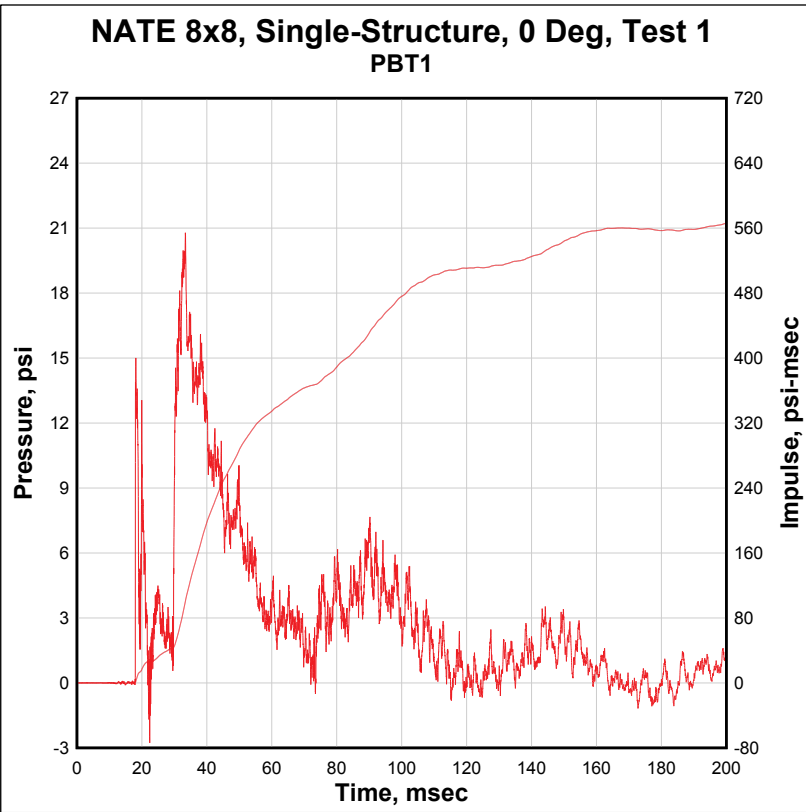
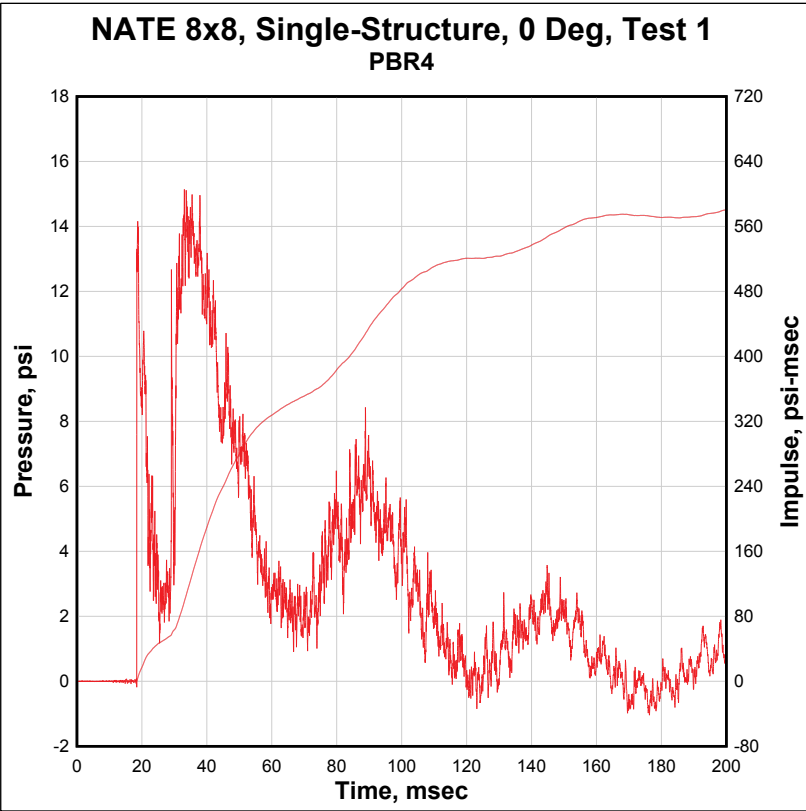


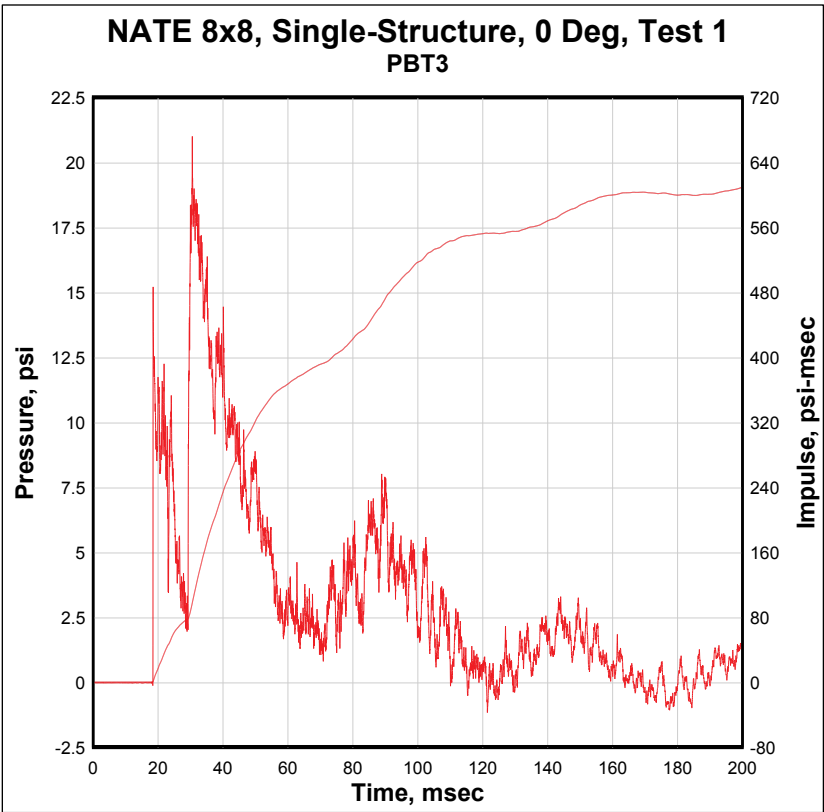
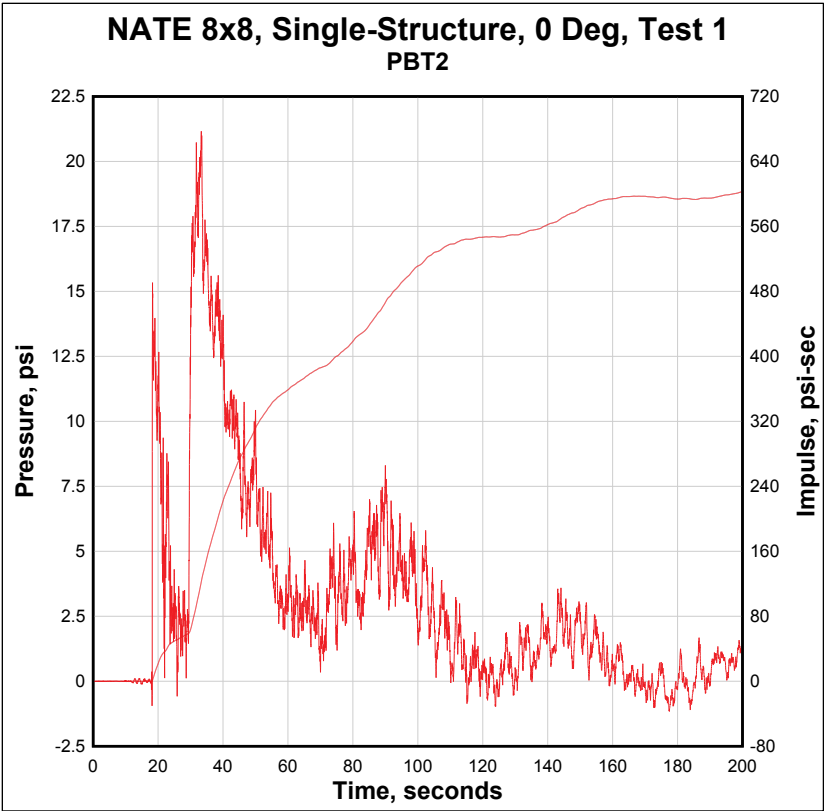


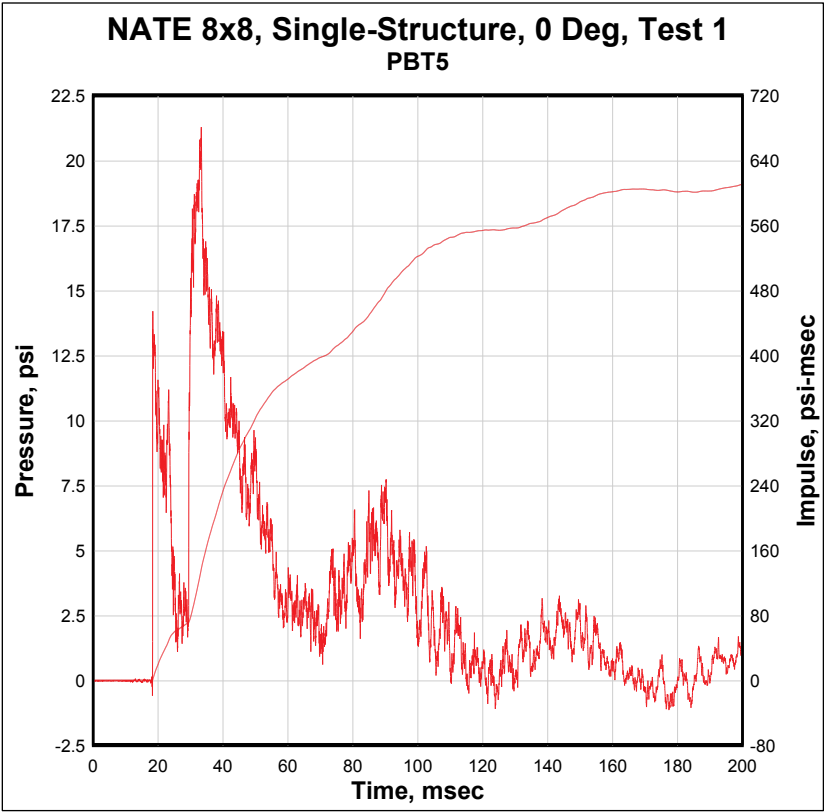
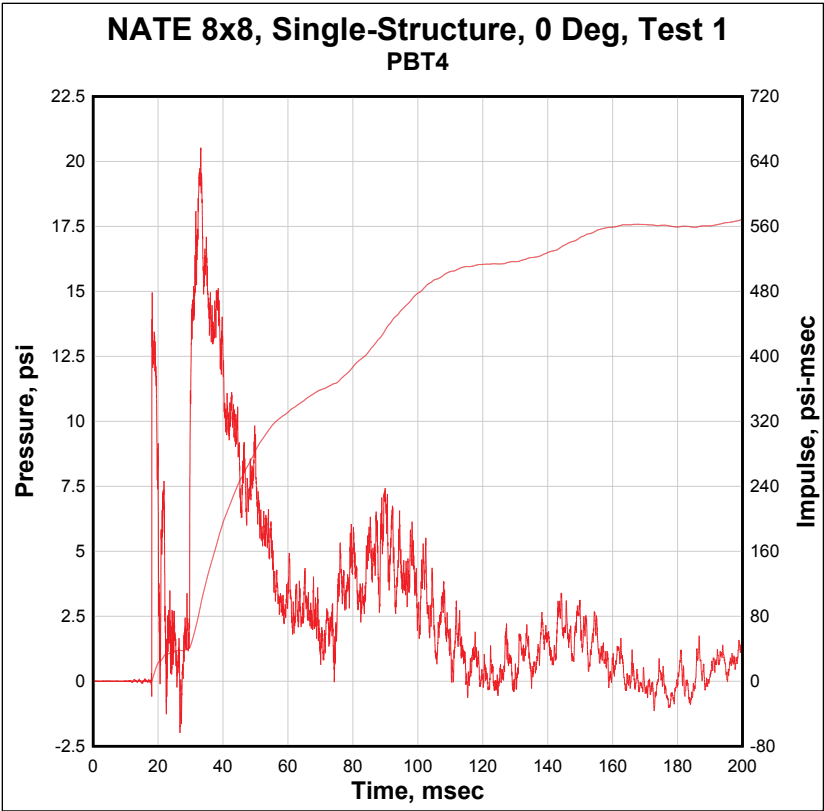


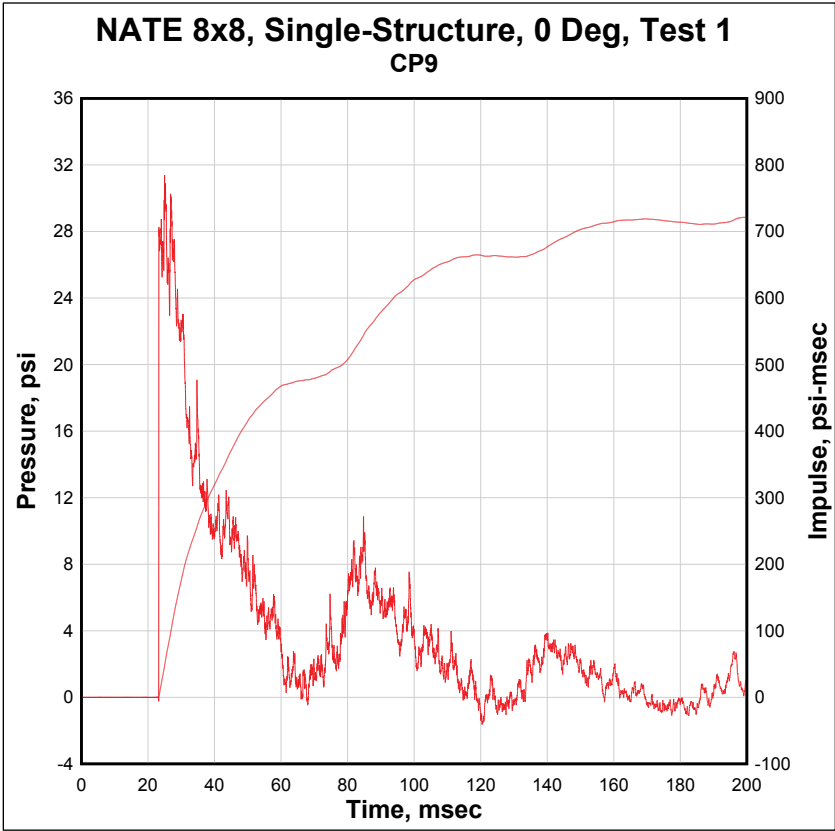
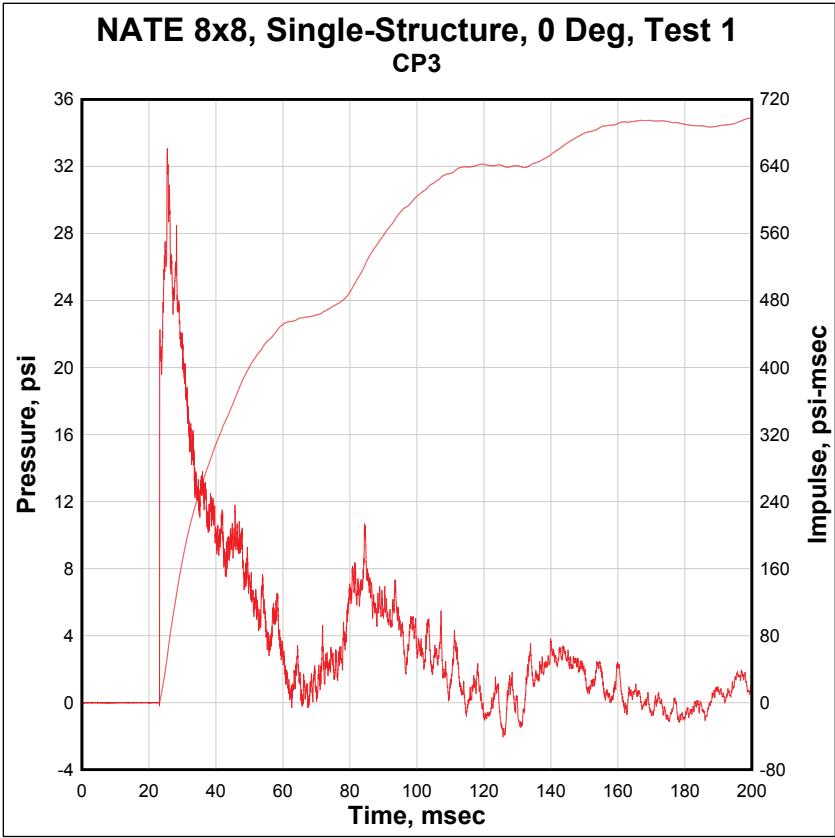




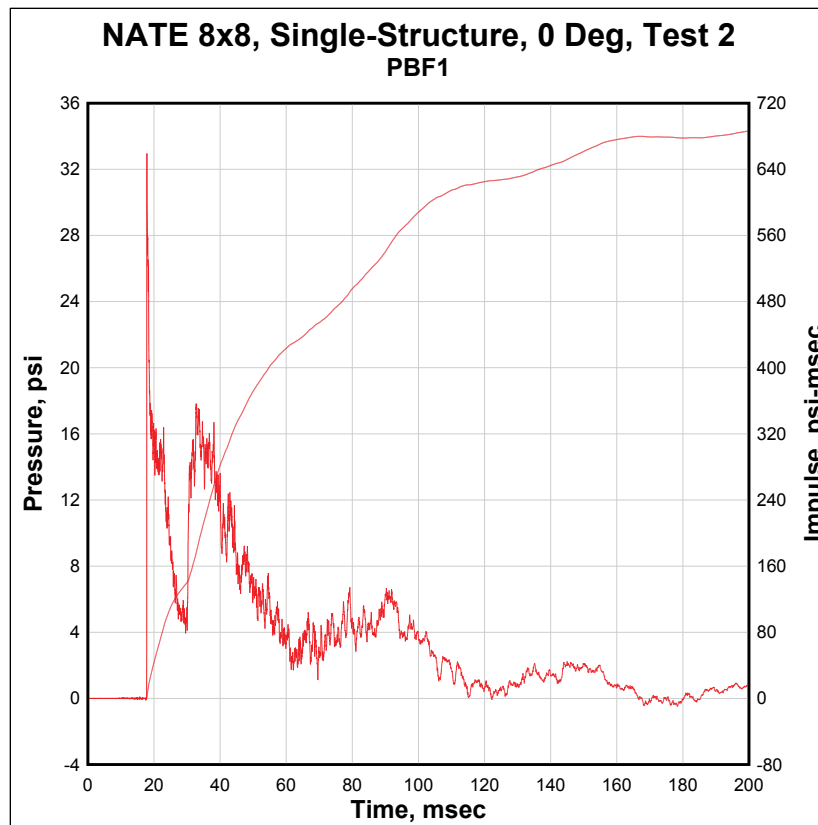


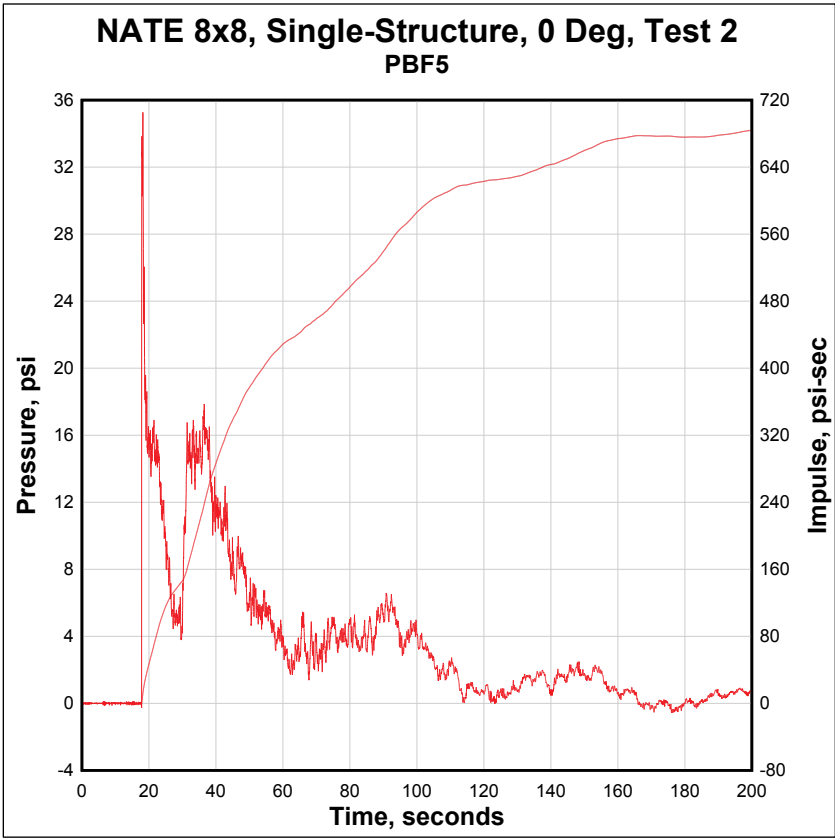
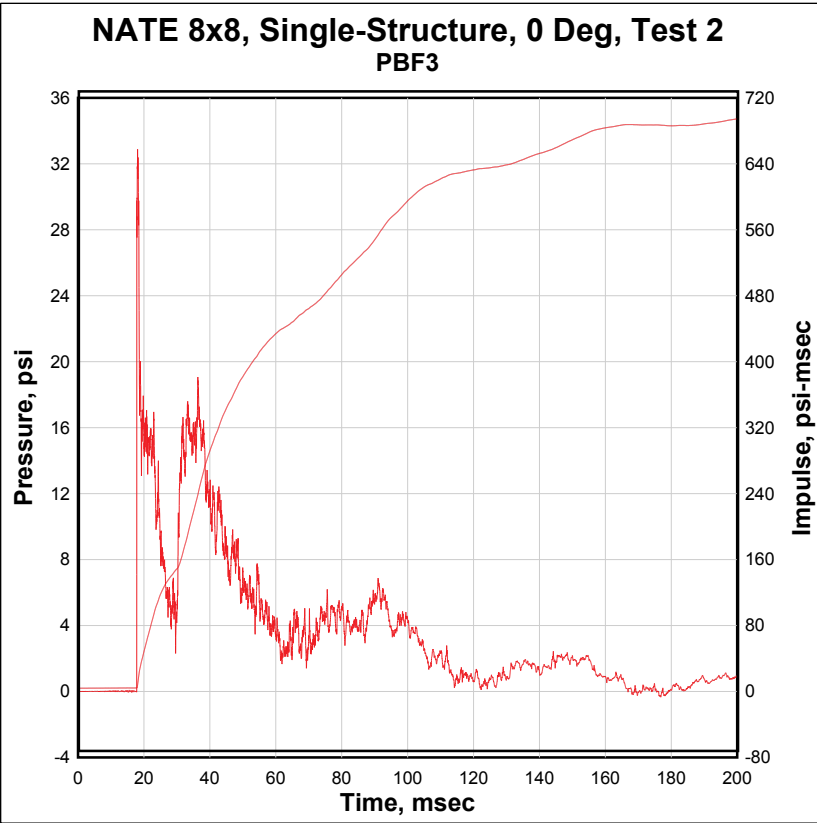


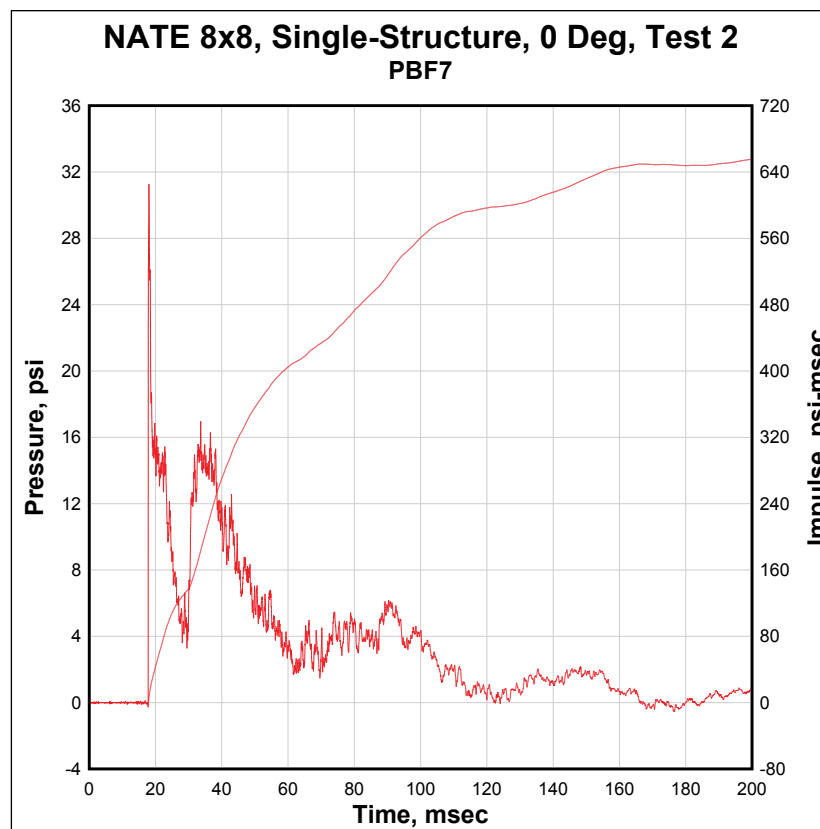
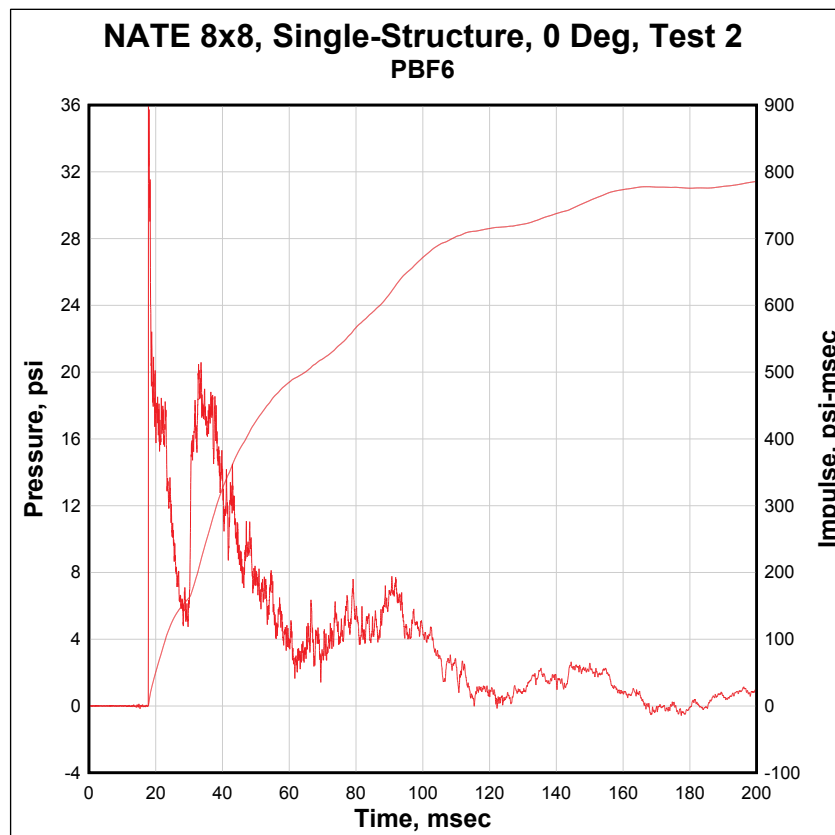


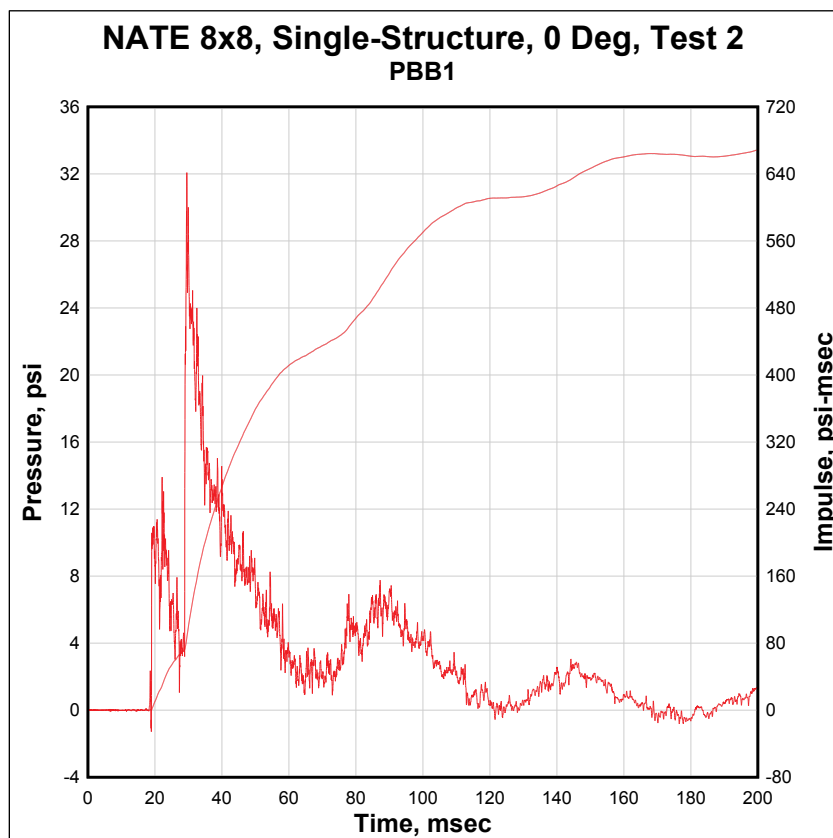
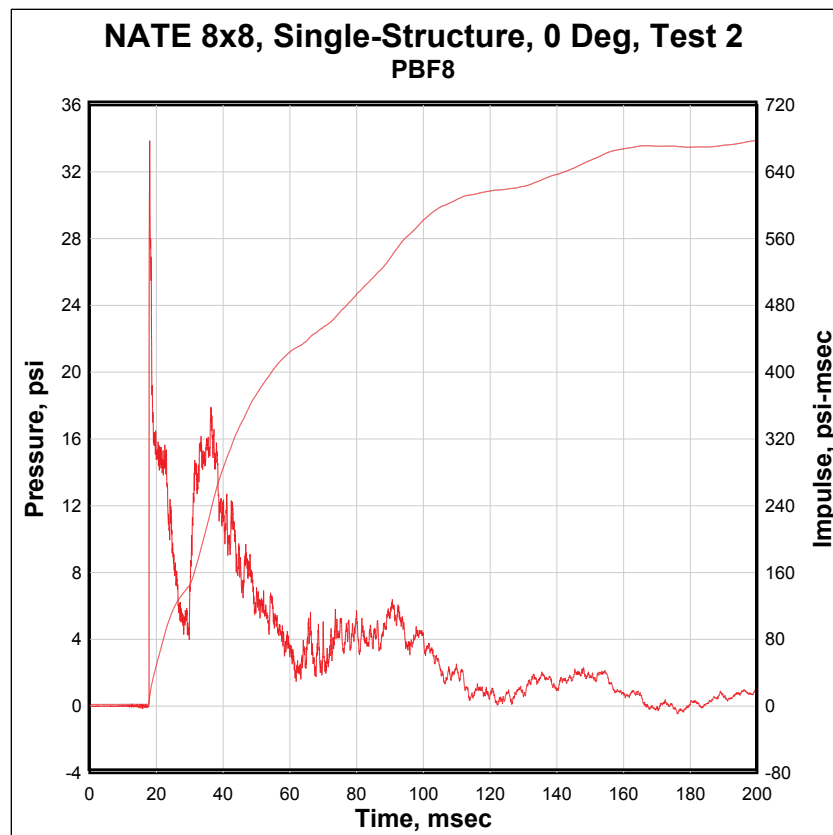


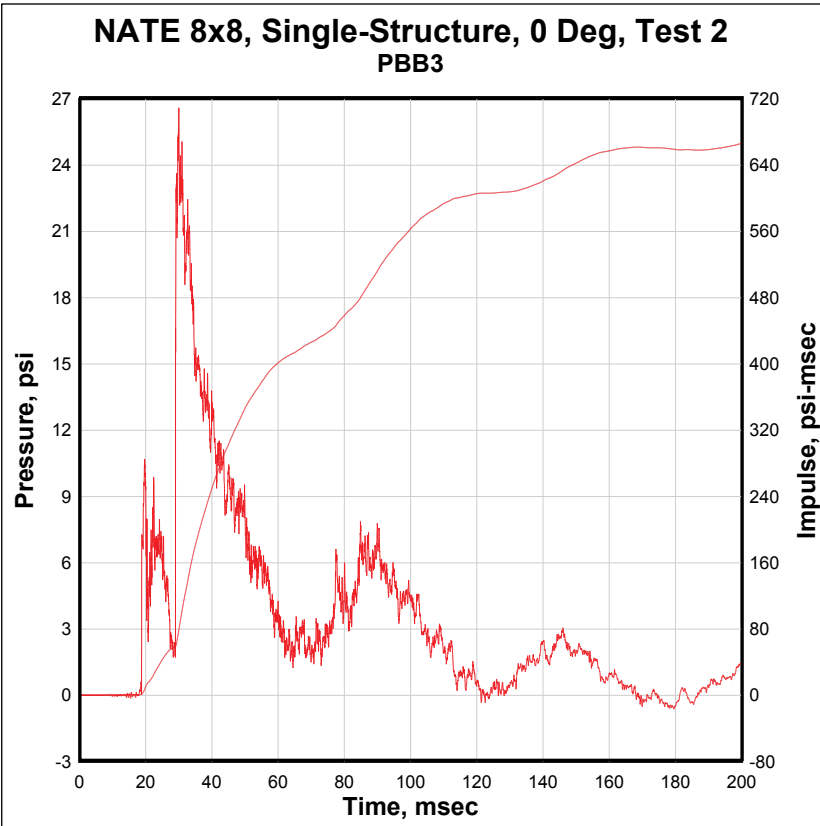
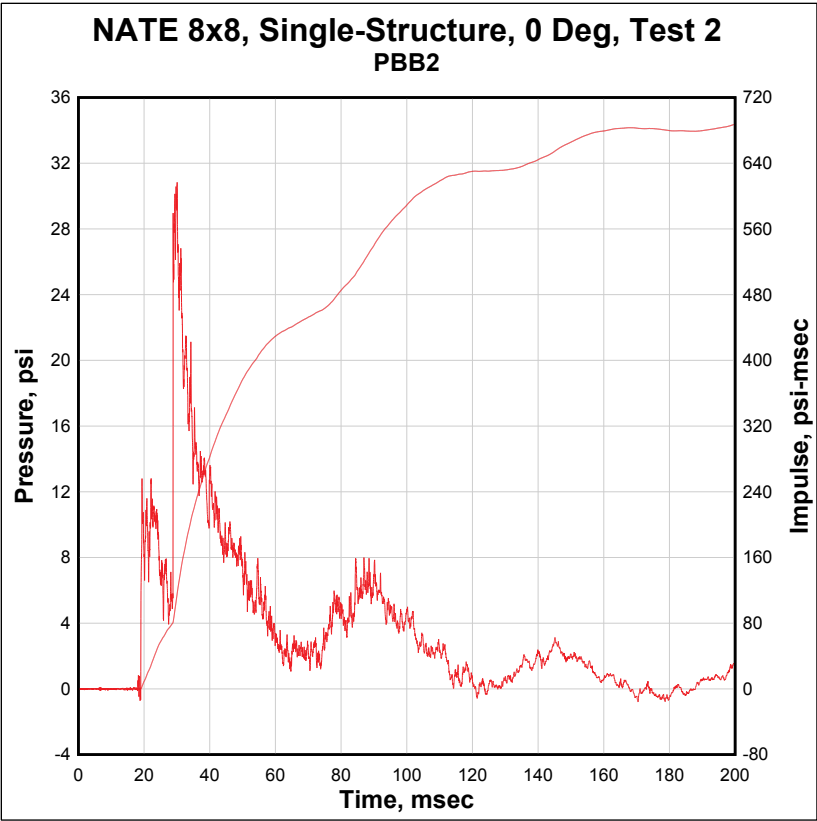
Appendix B: Pressure and Impulse Data from Test 2

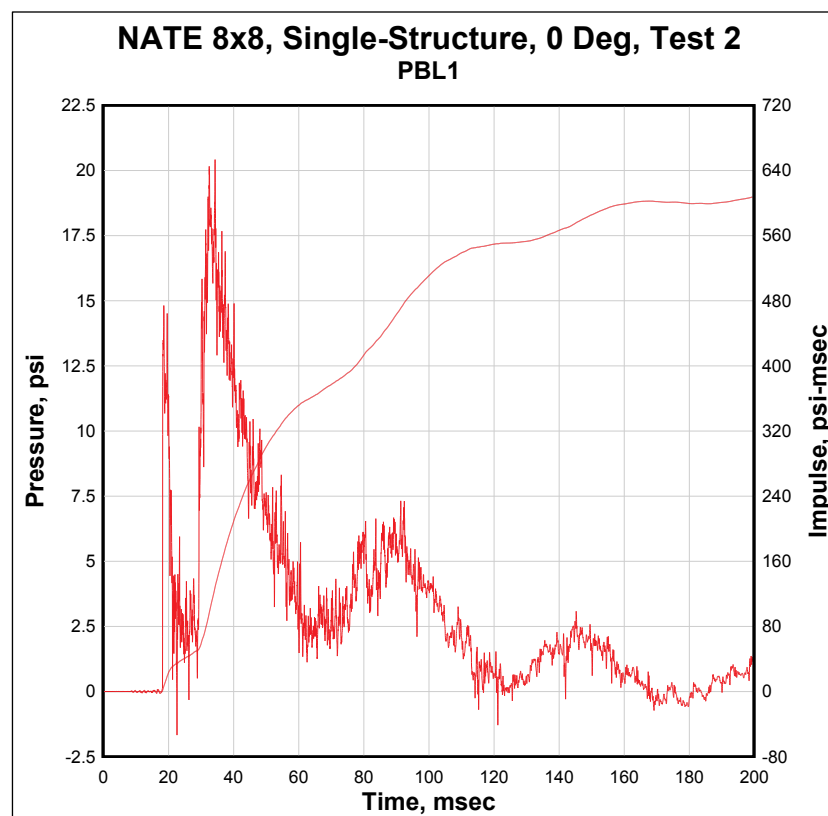
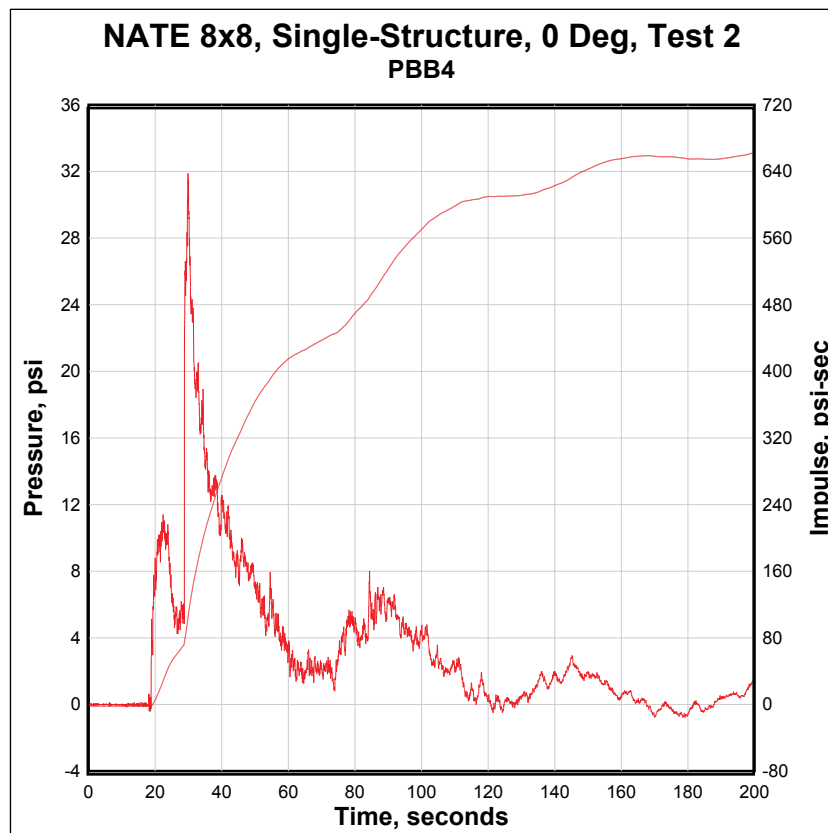


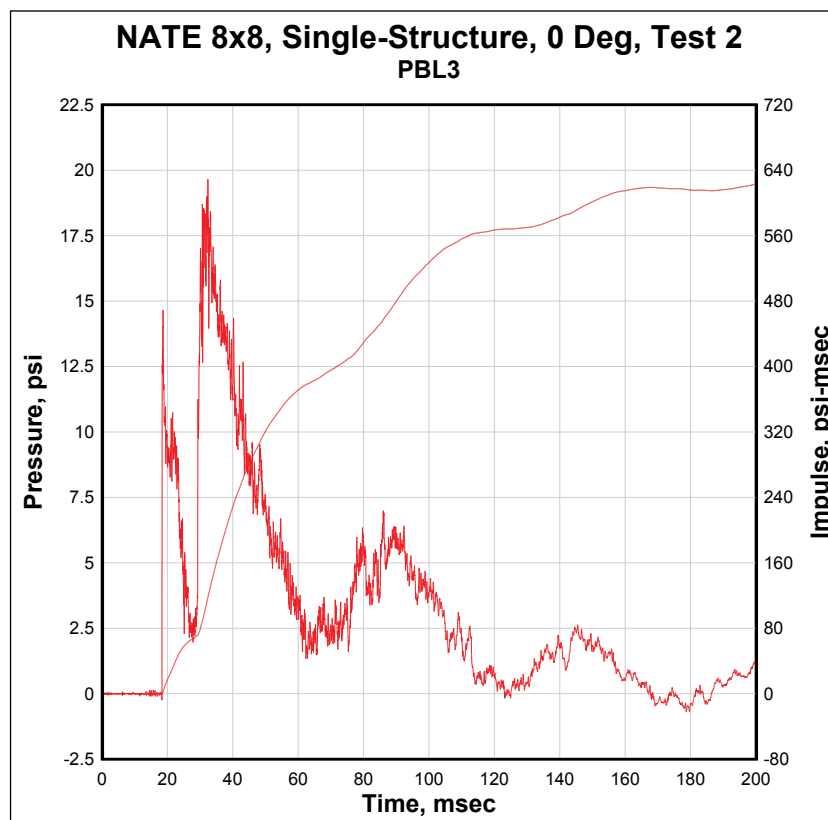
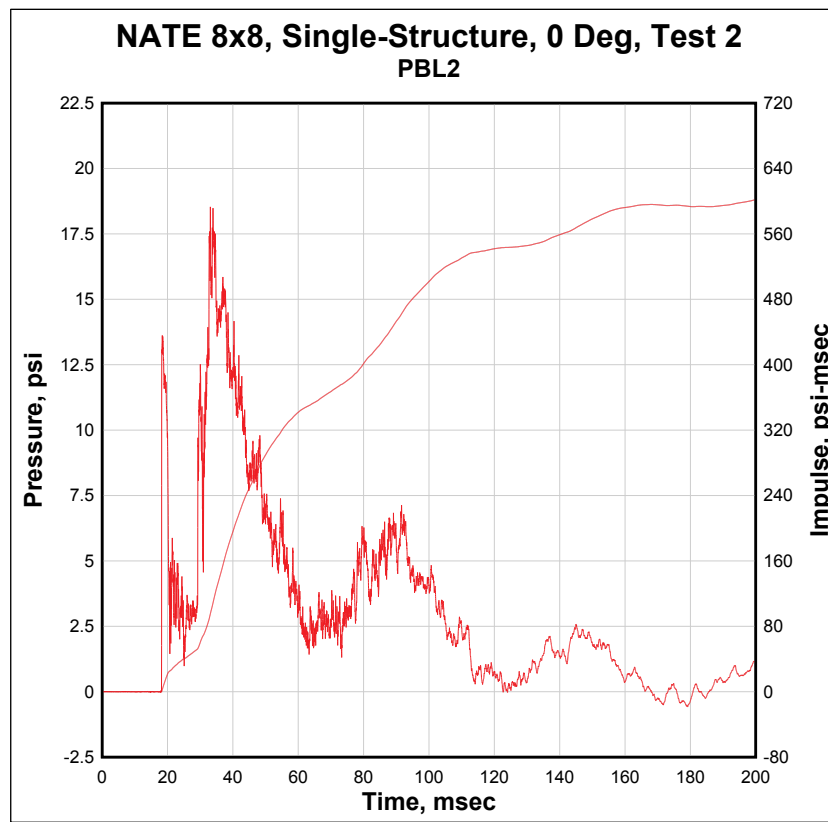


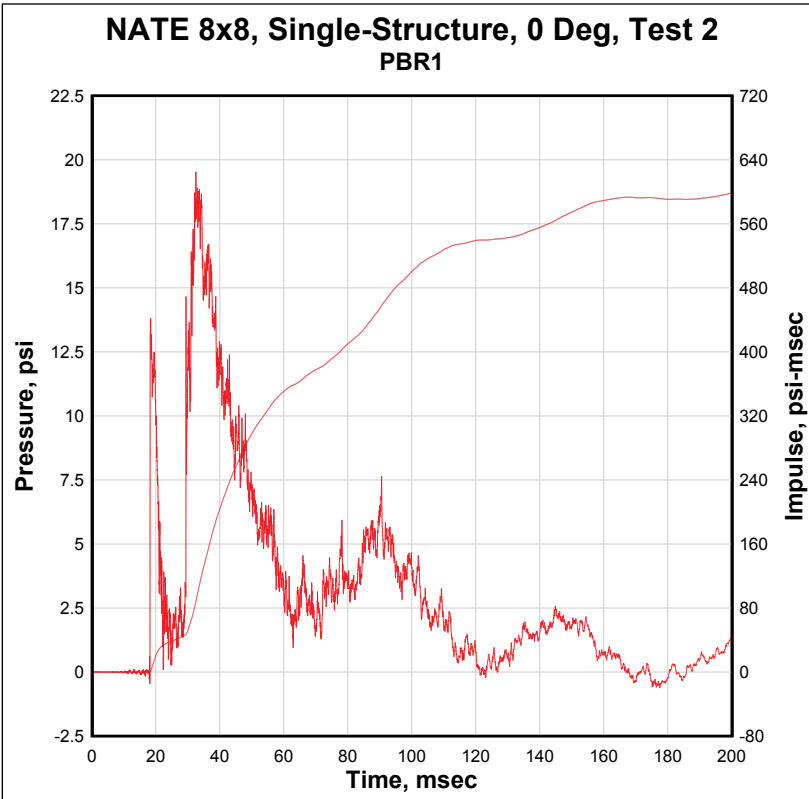
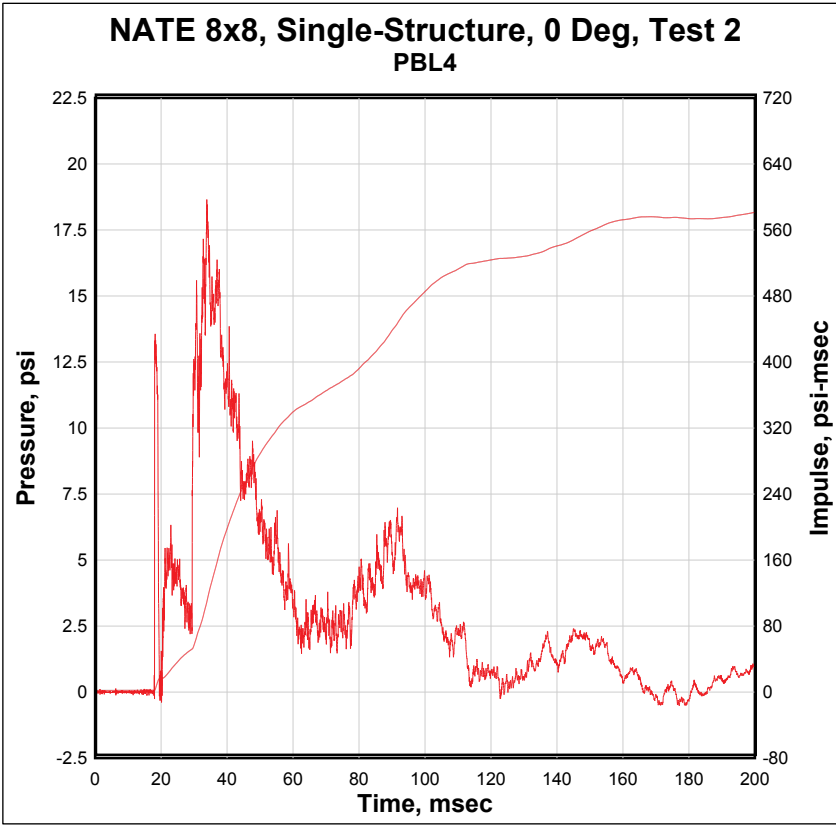


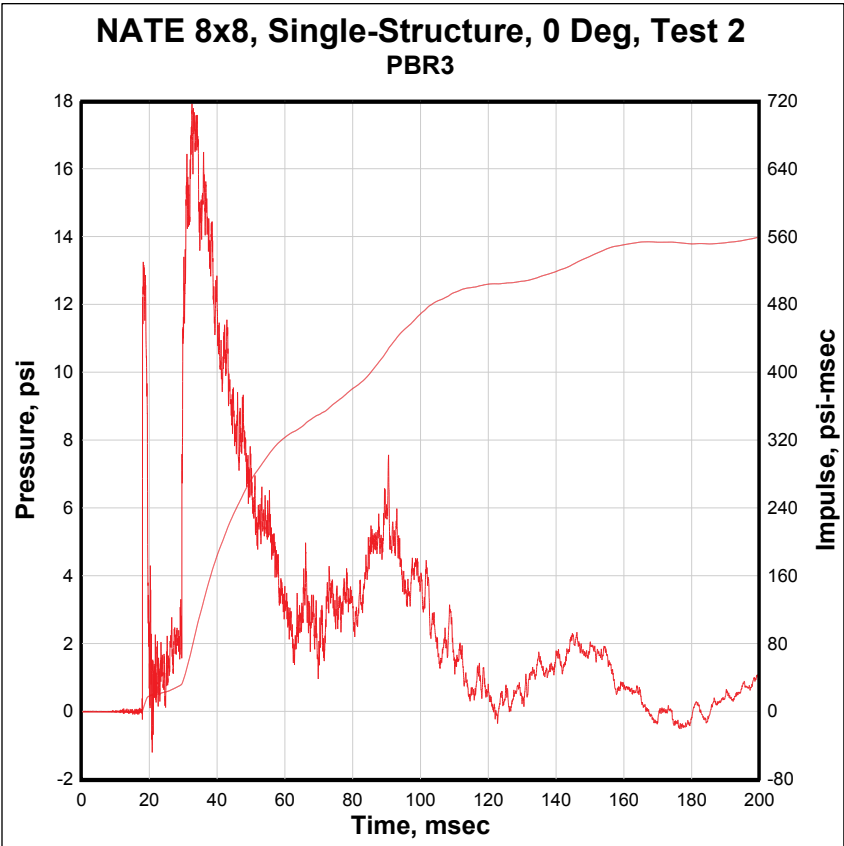
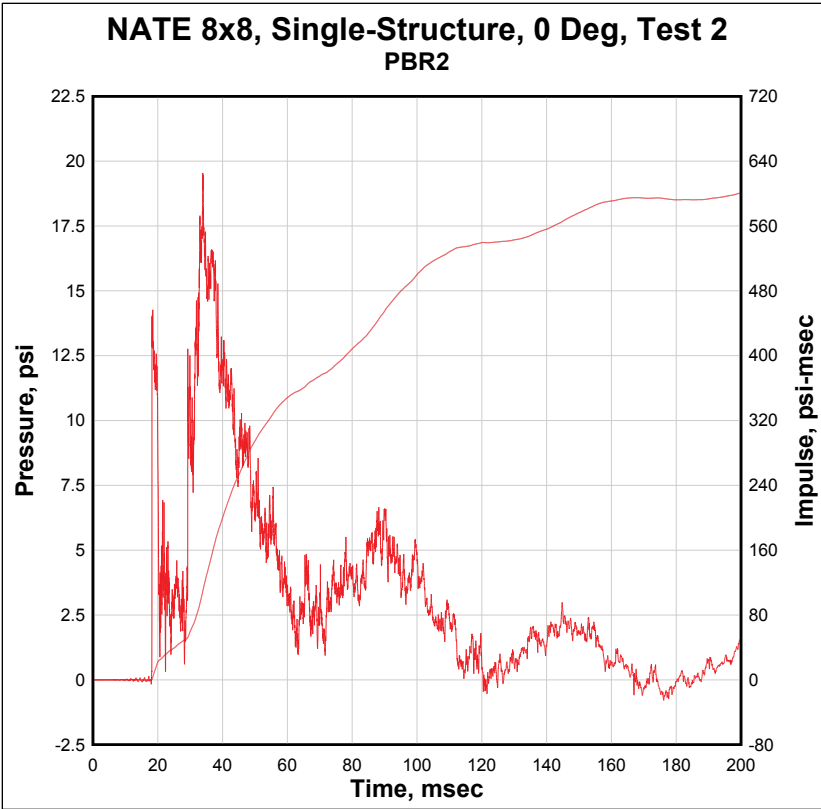


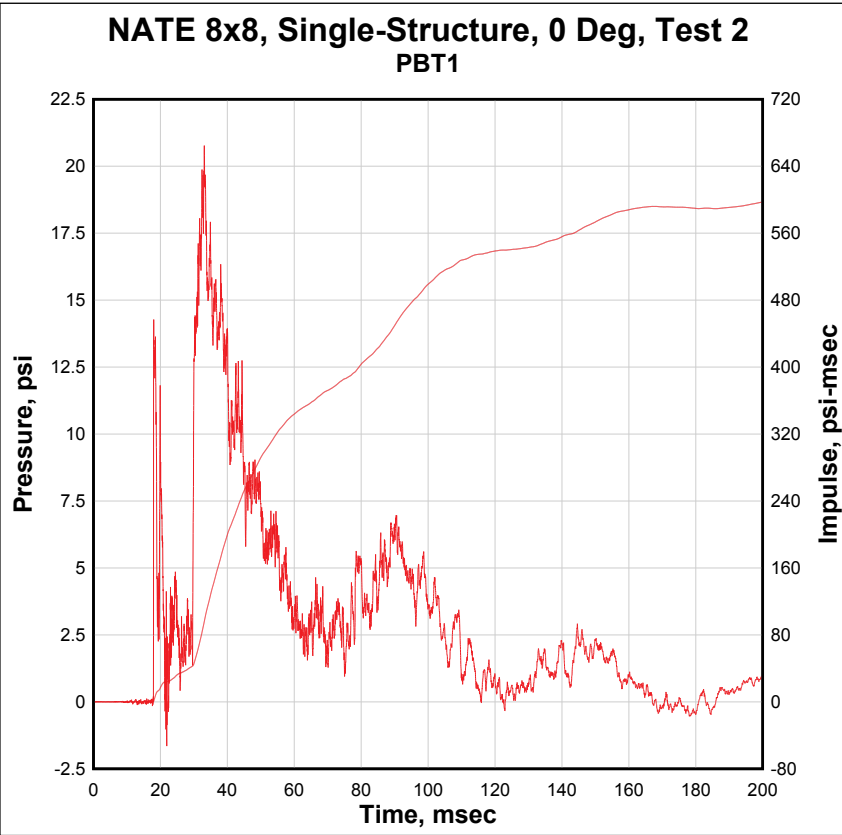
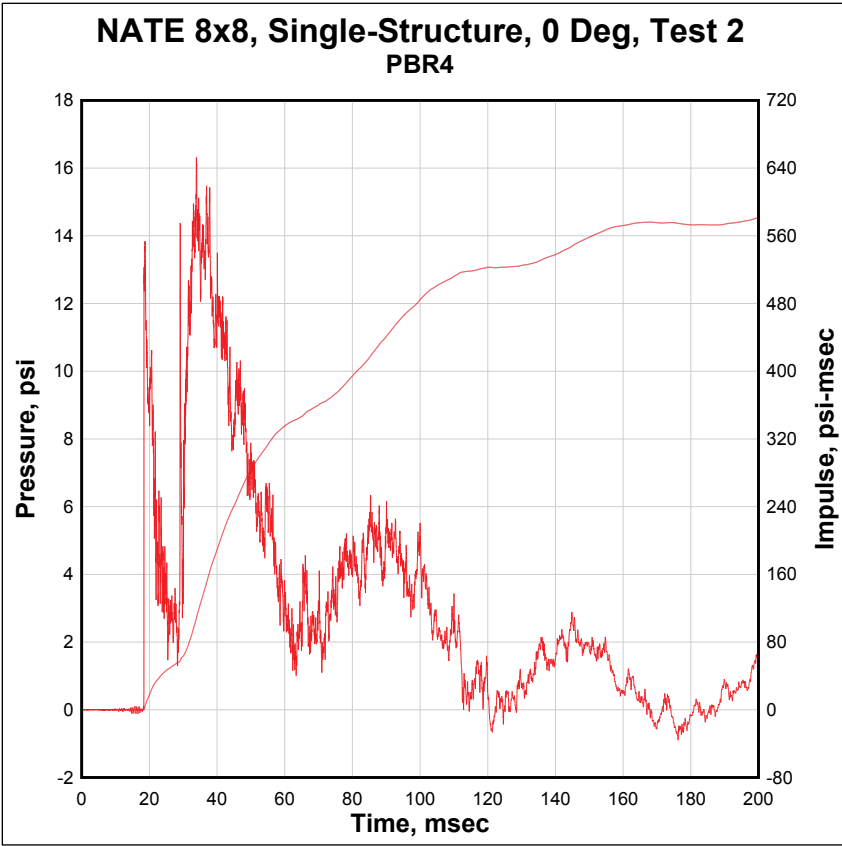


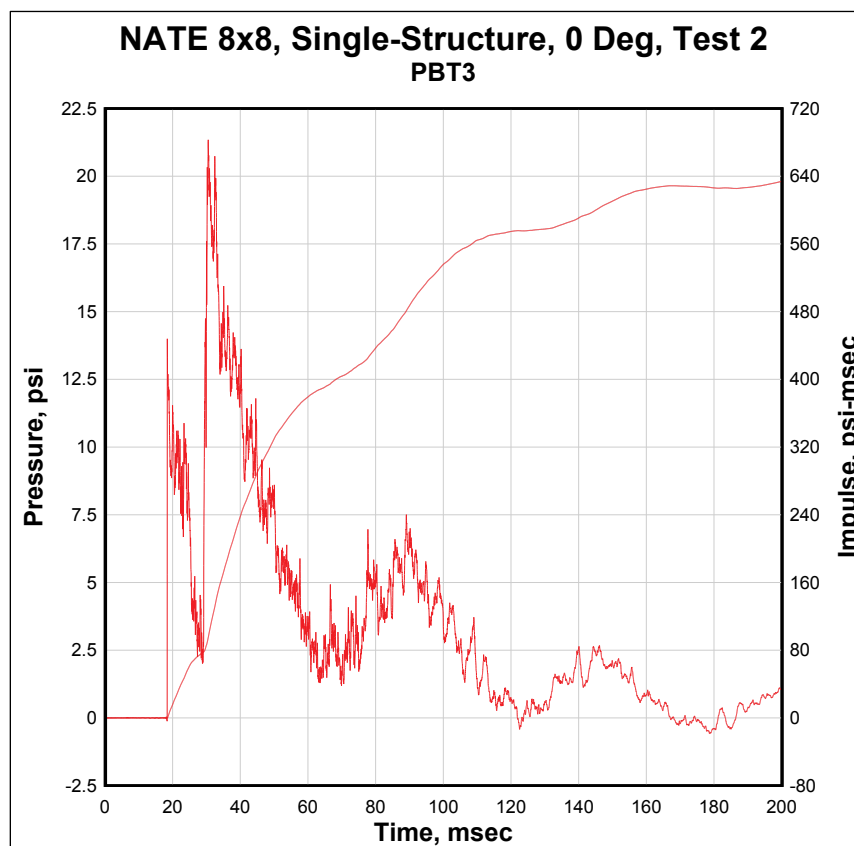
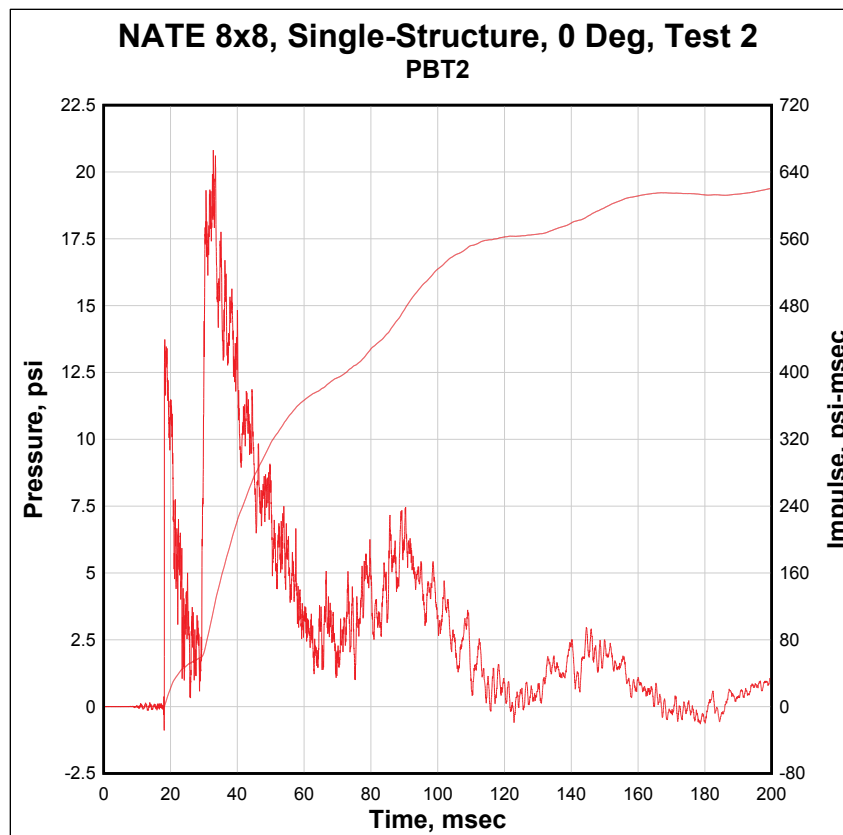


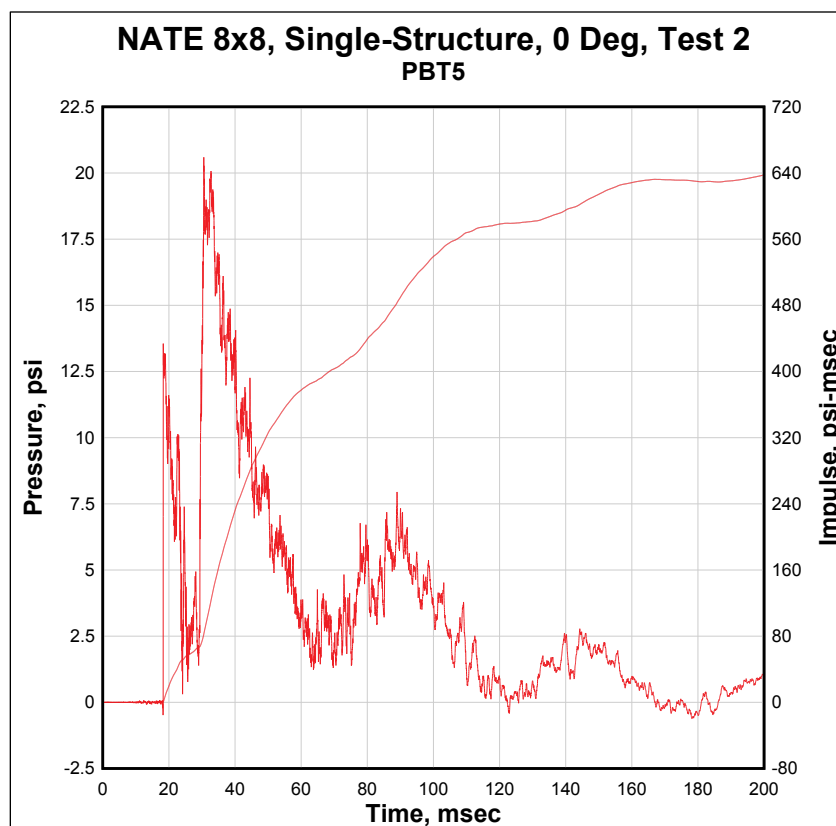
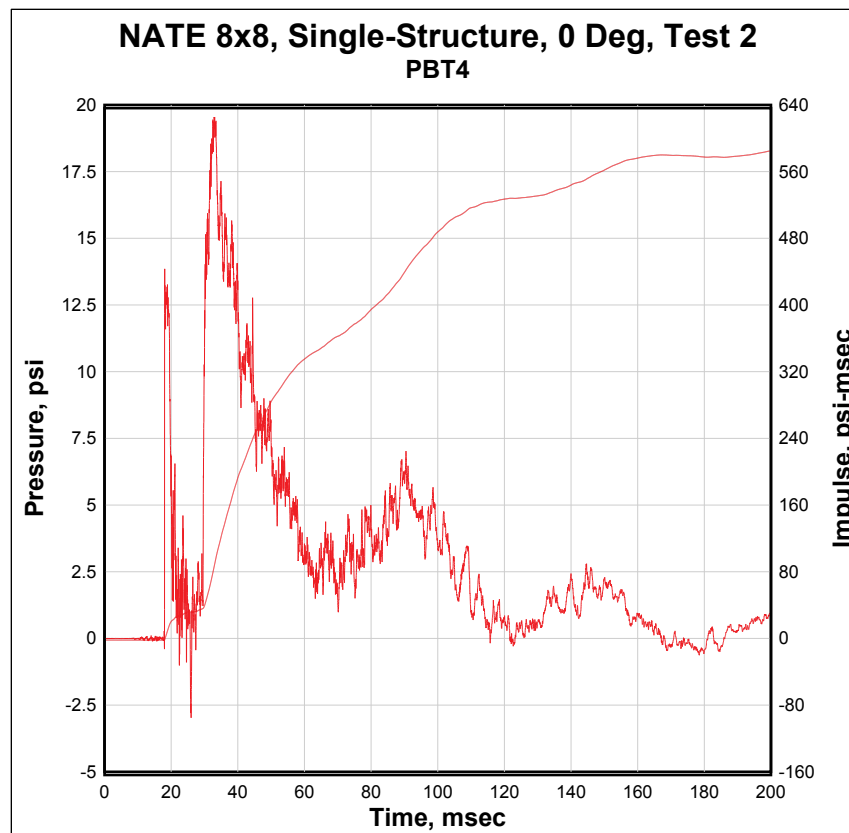


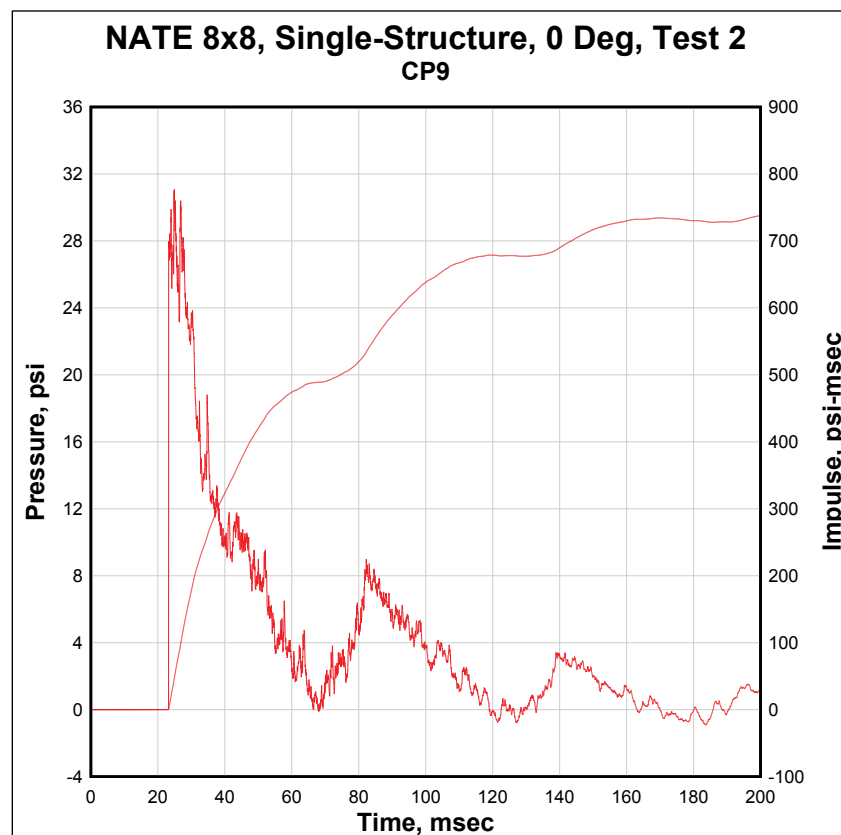
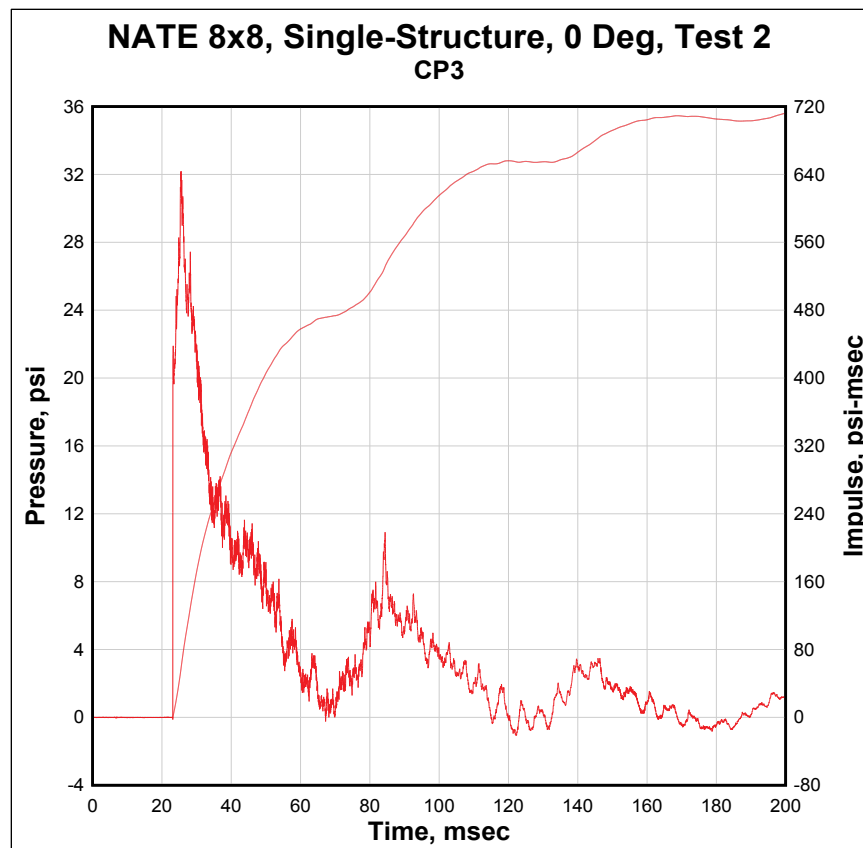




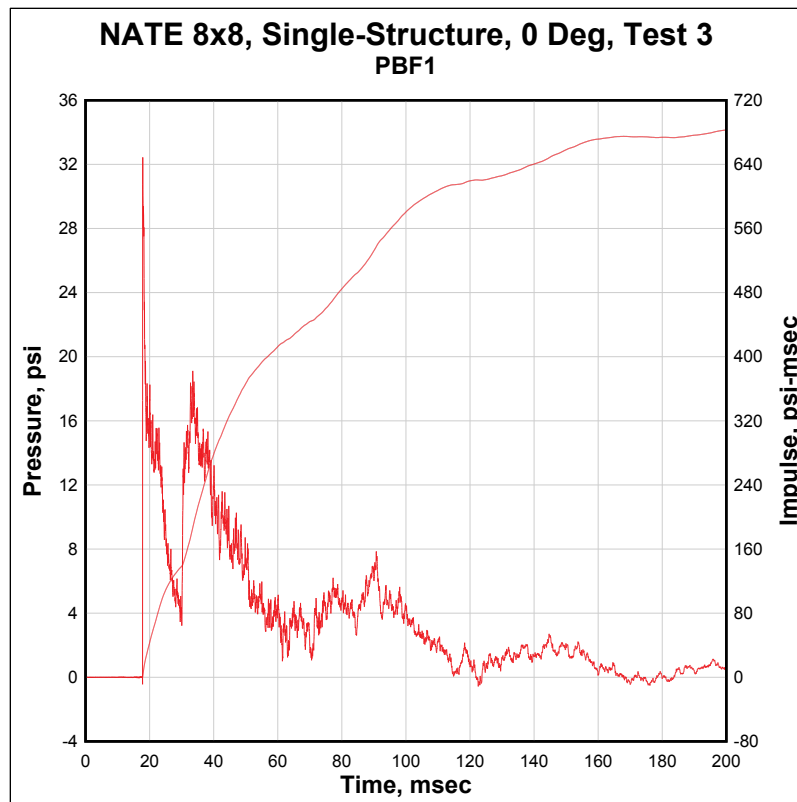


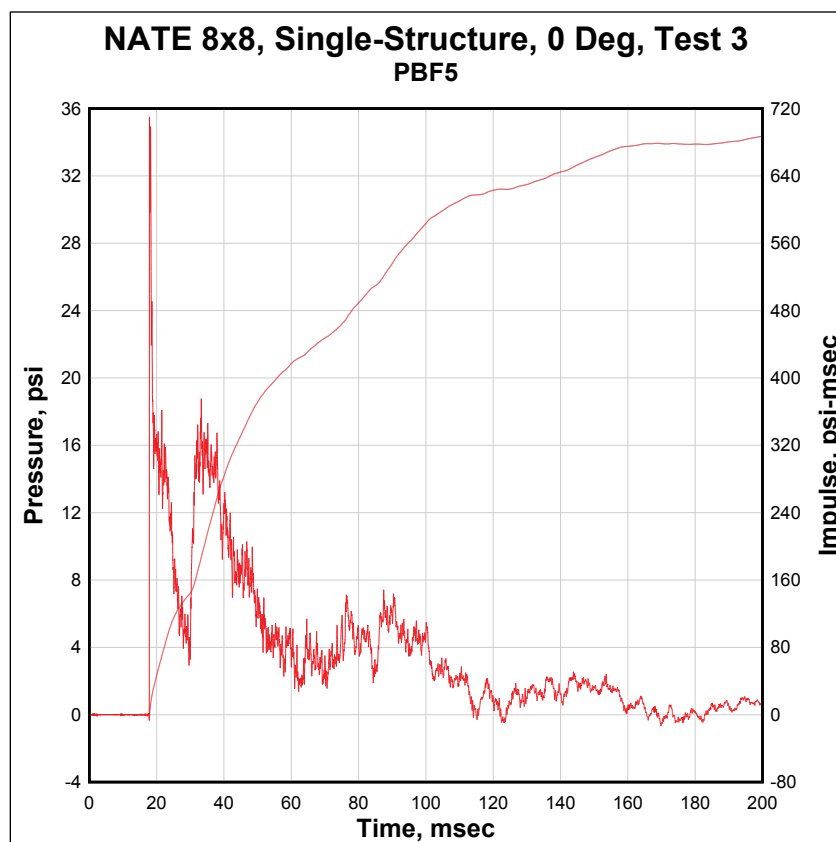
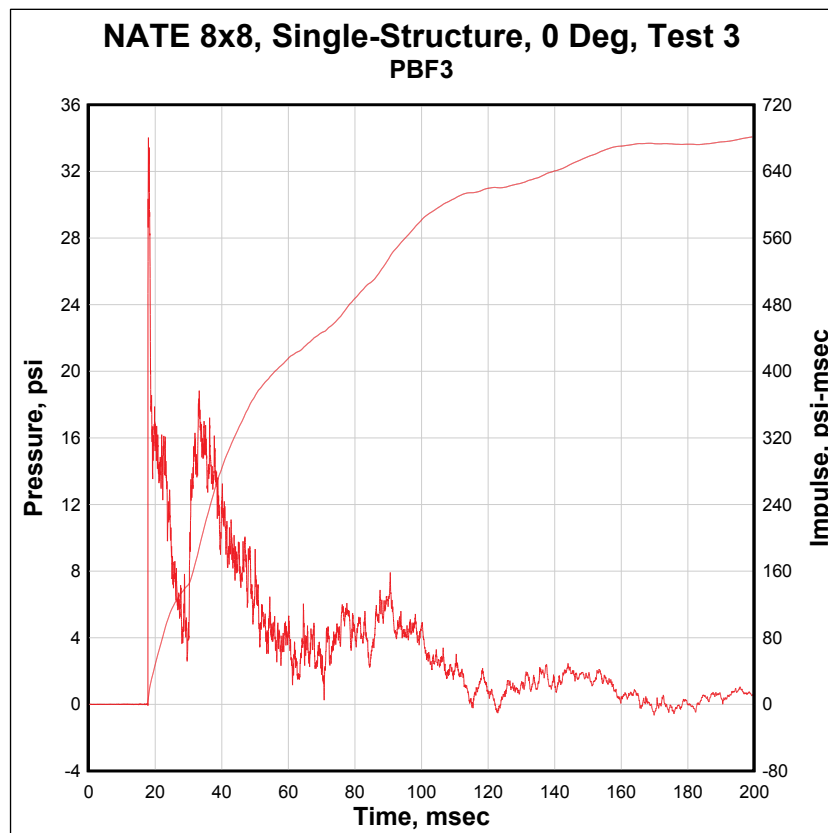


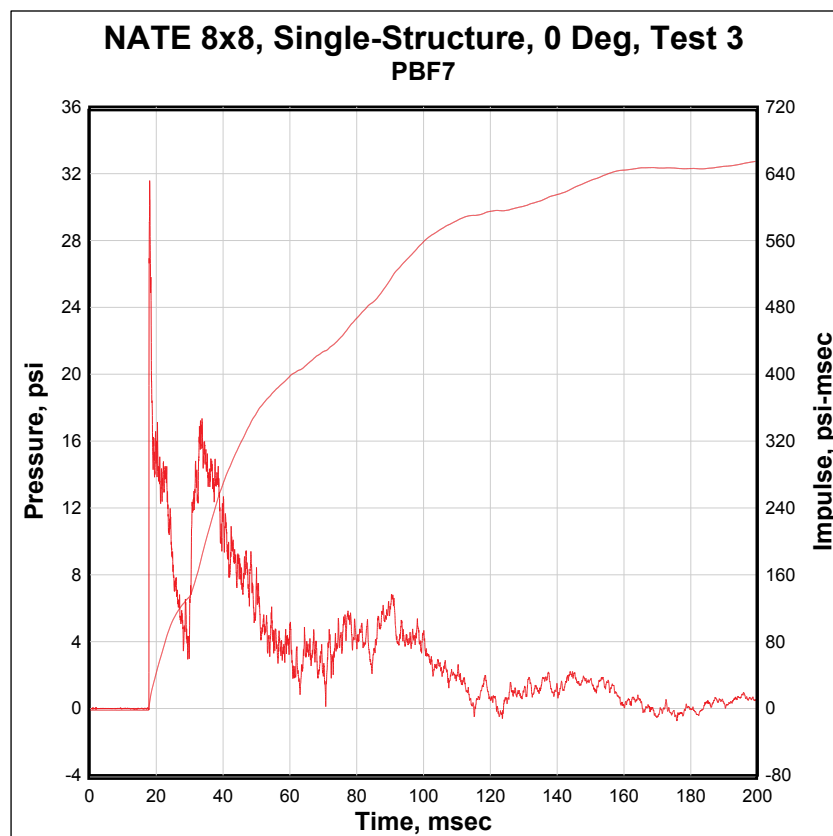
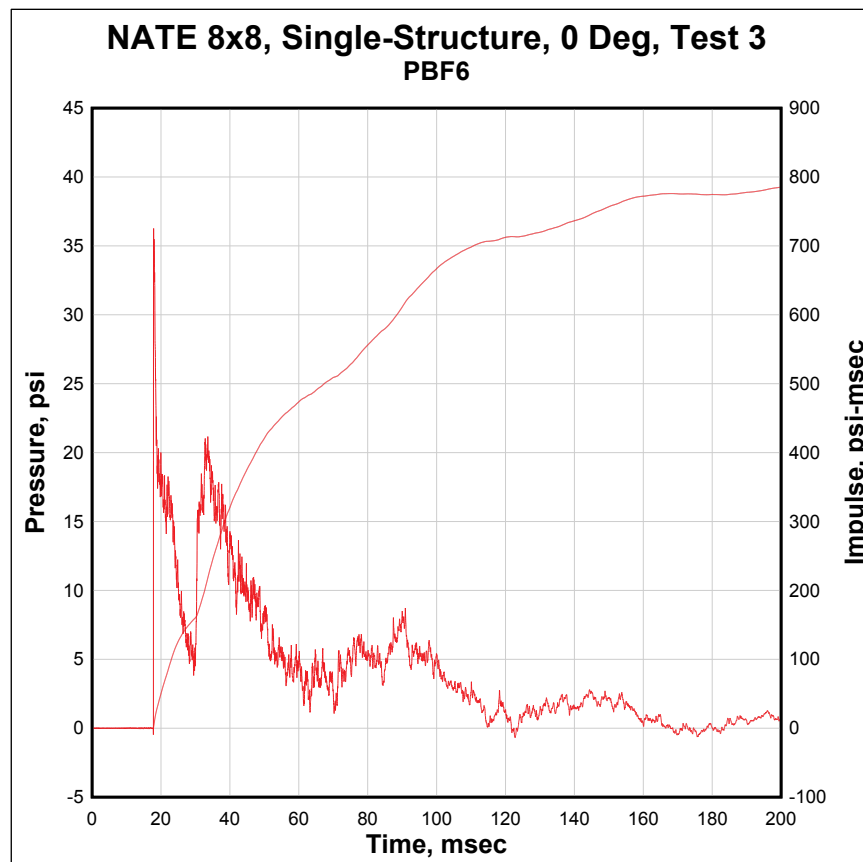


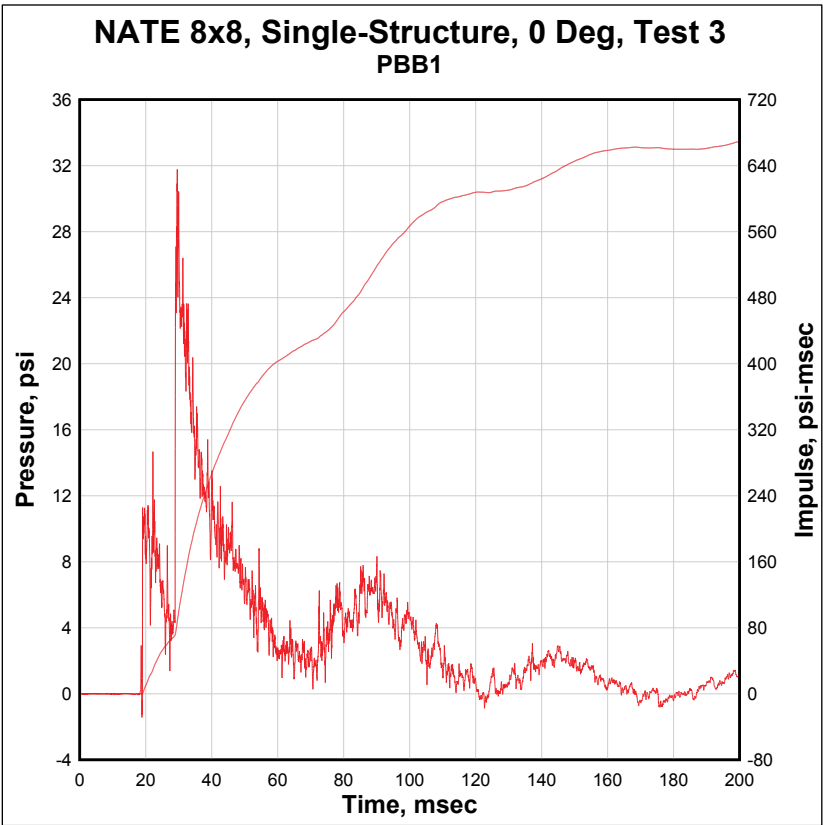
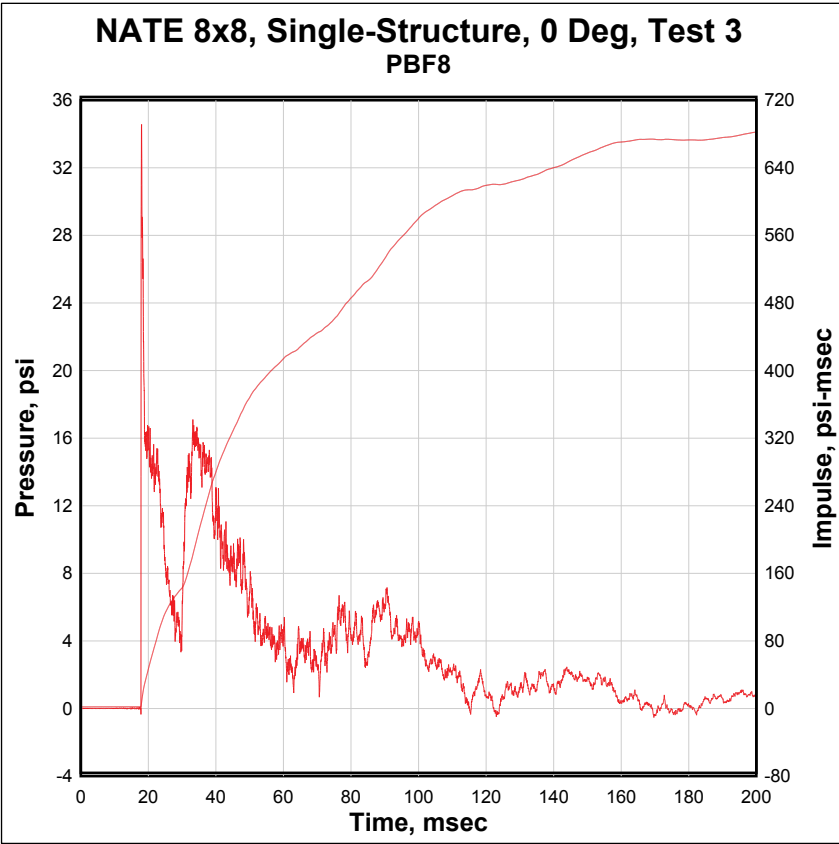


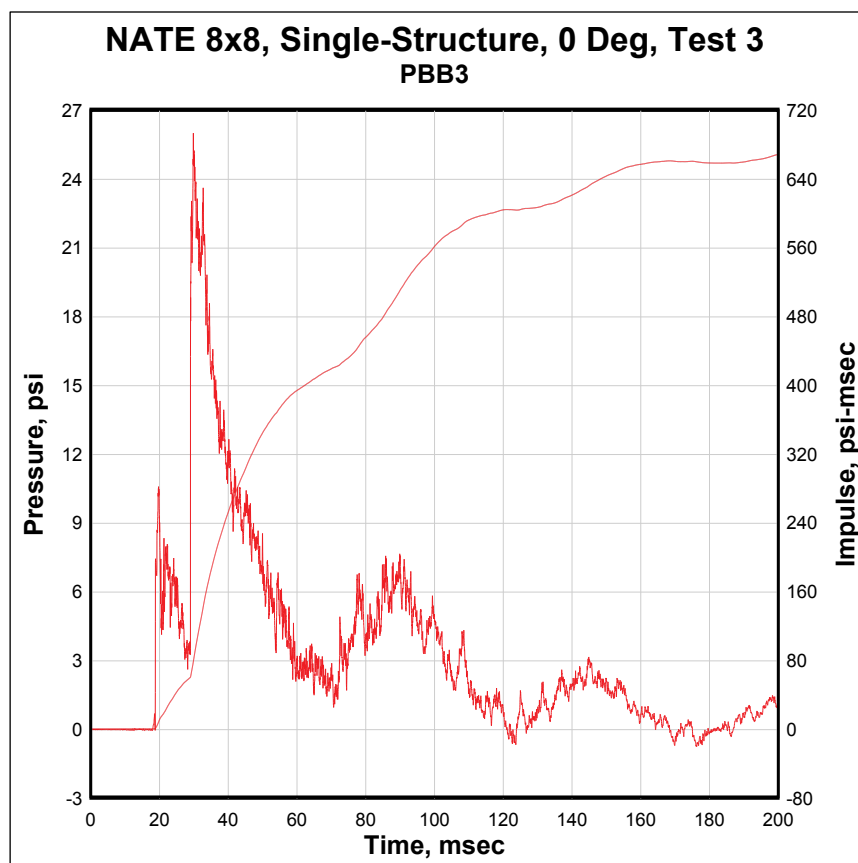
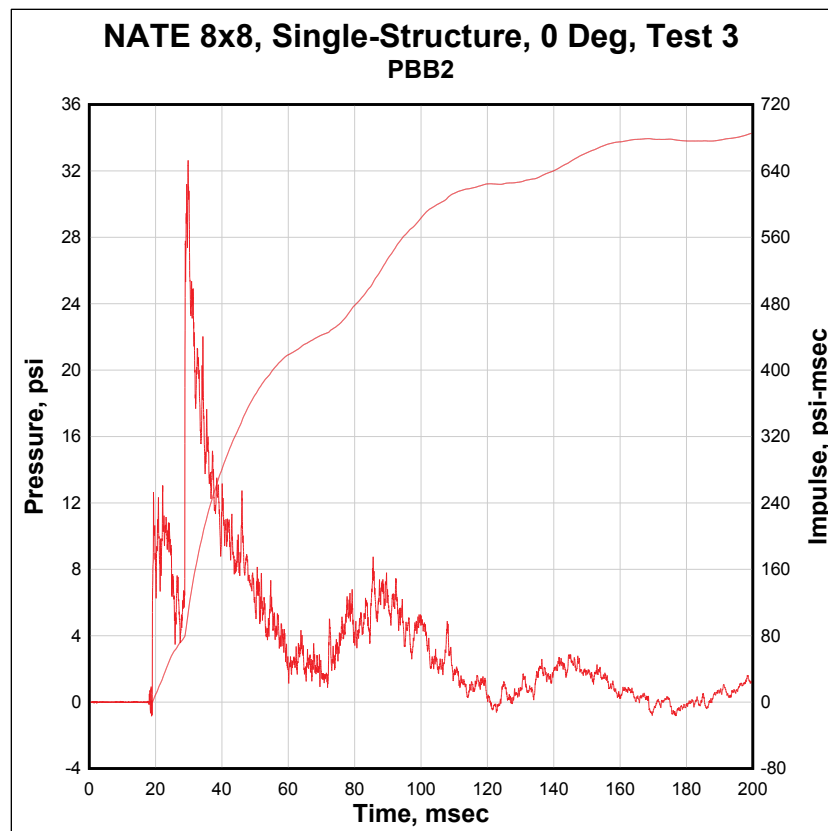
Appendix C: Pressure and Impulse Data from Test 3

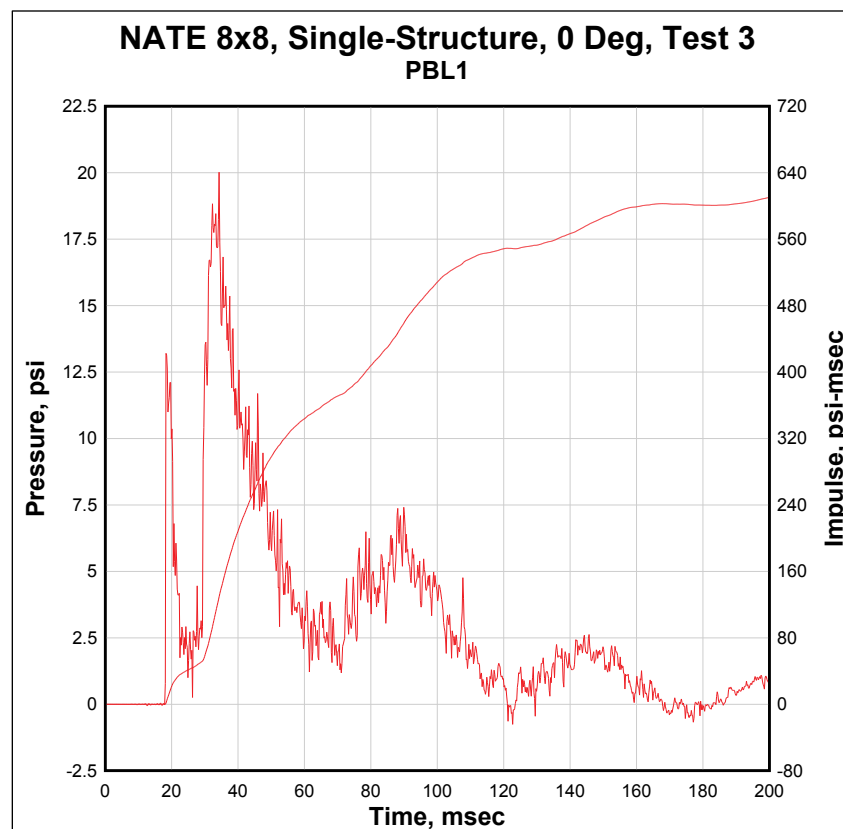
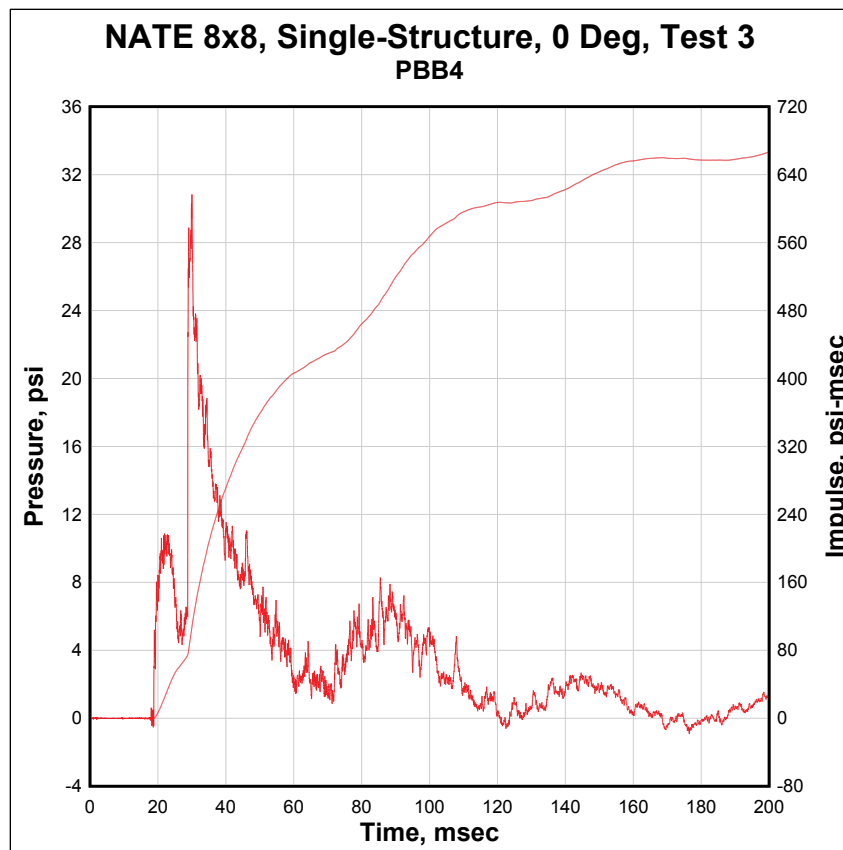


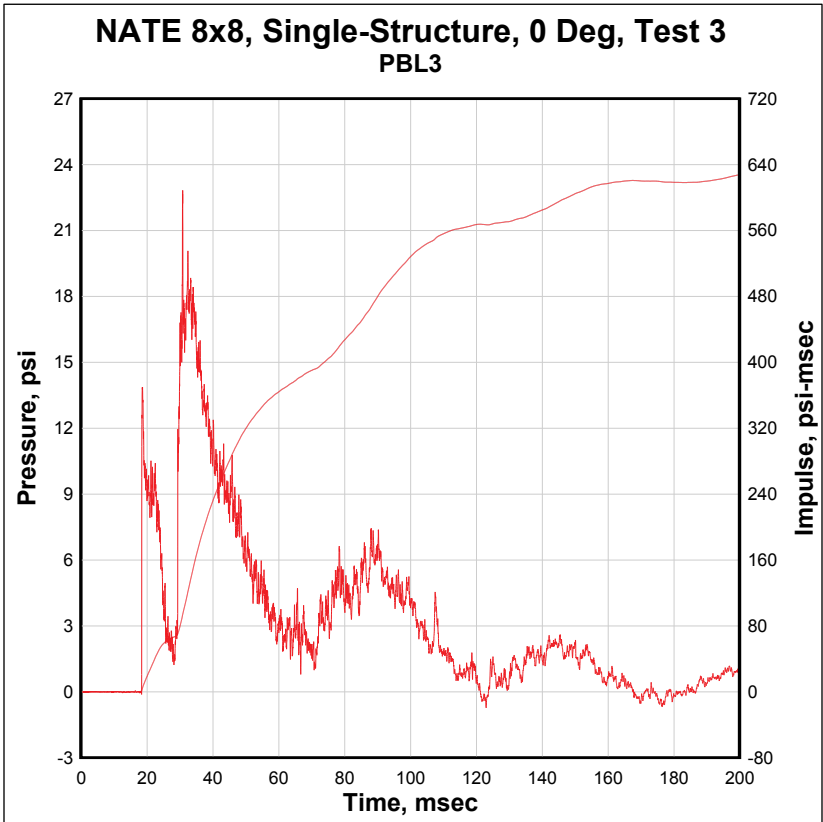
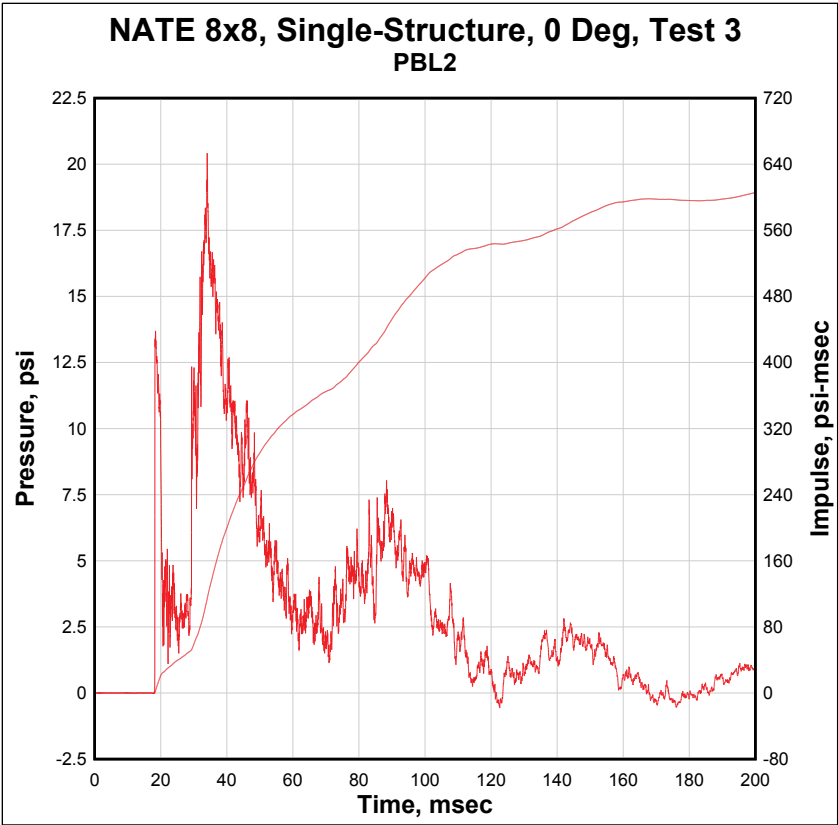


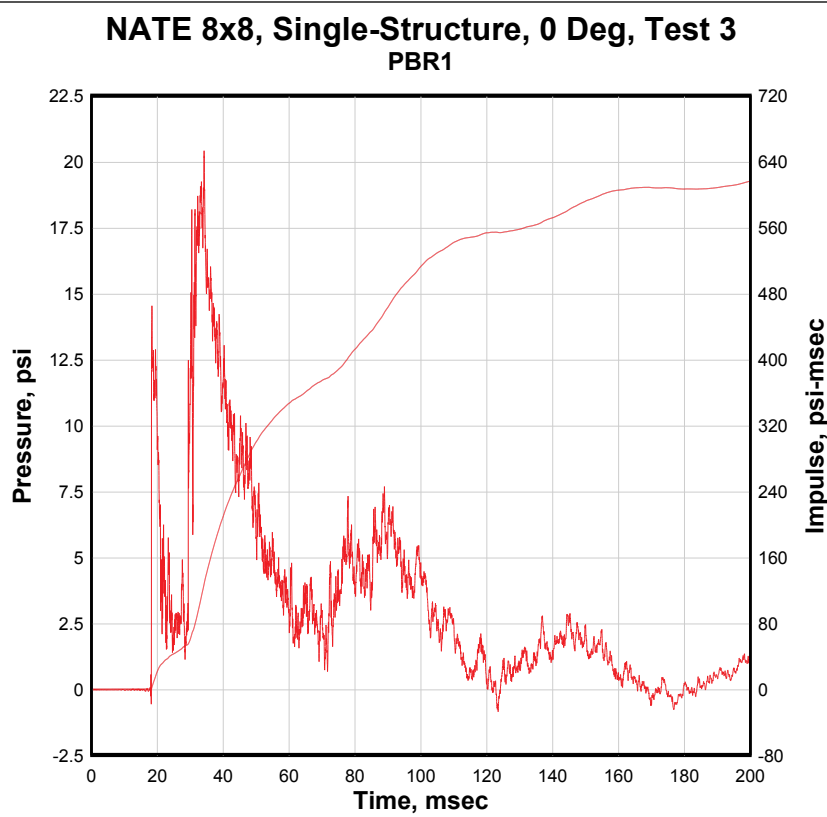
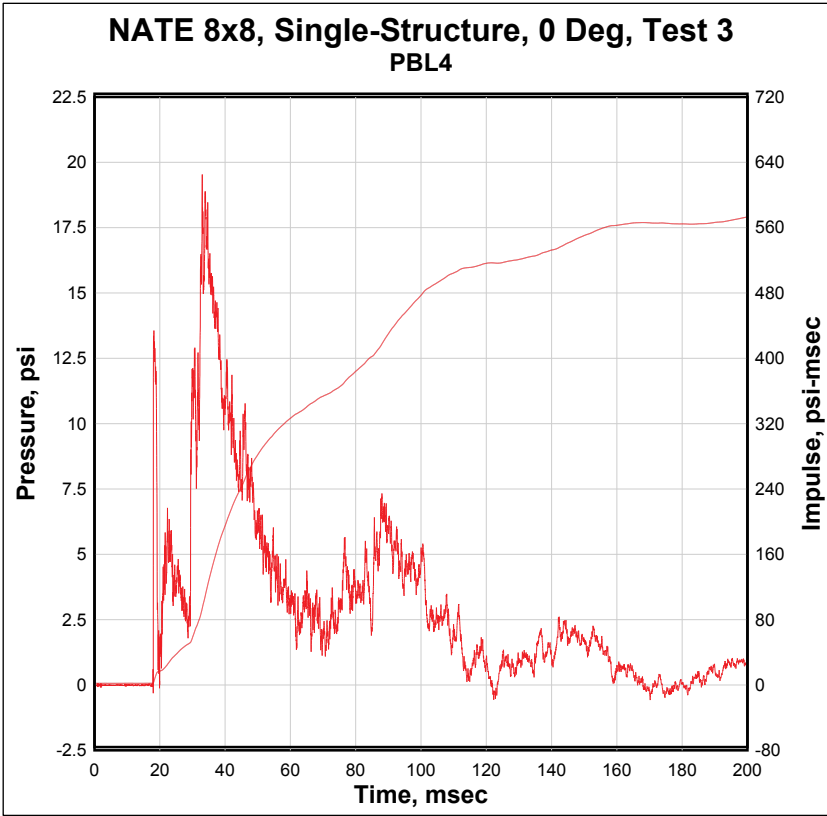


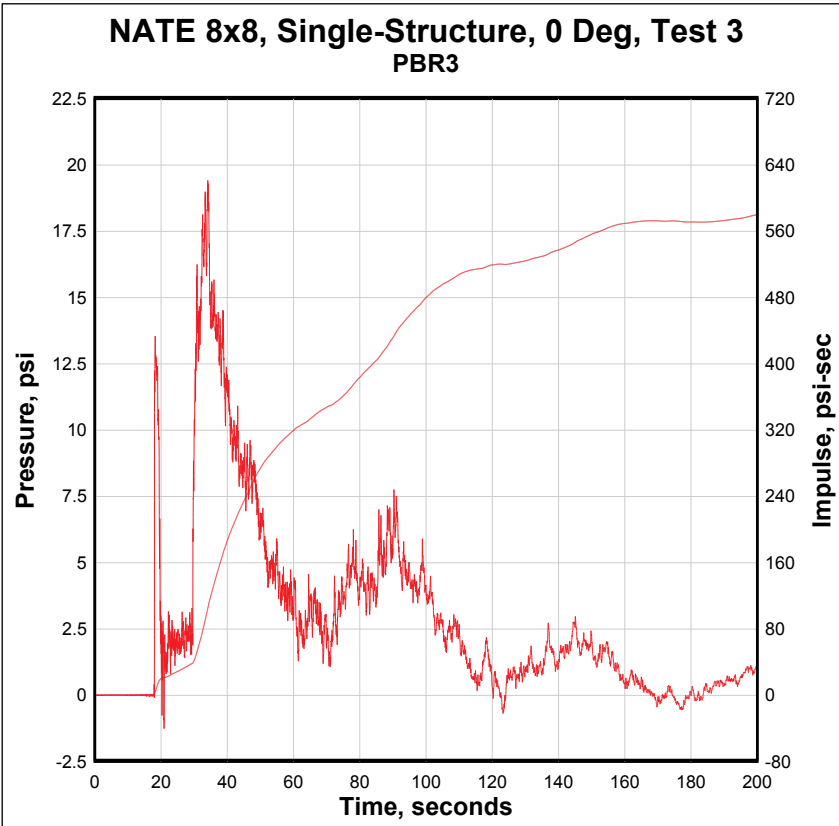
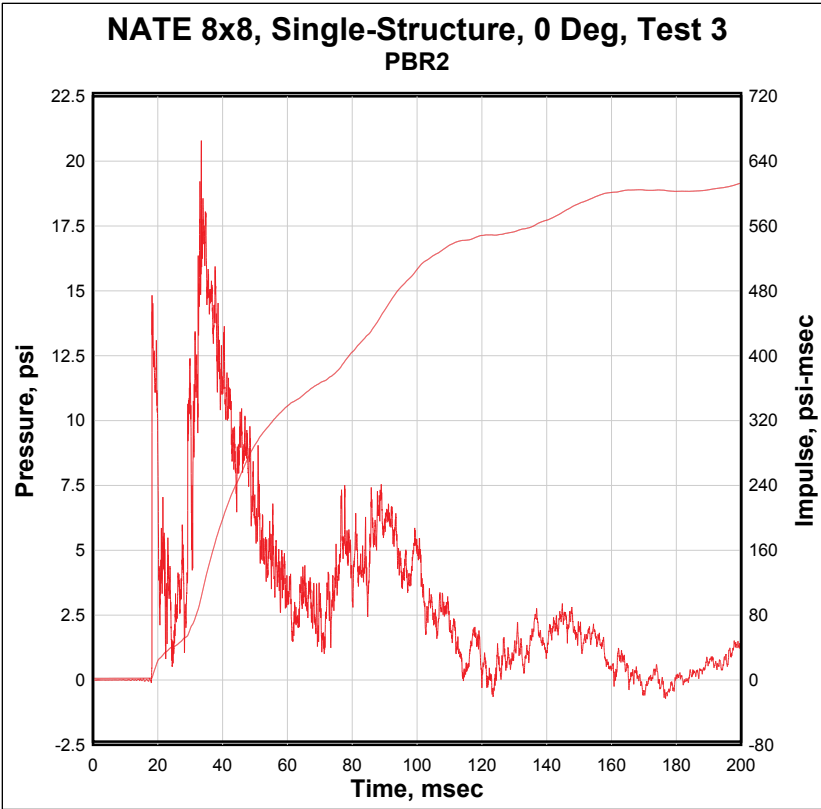


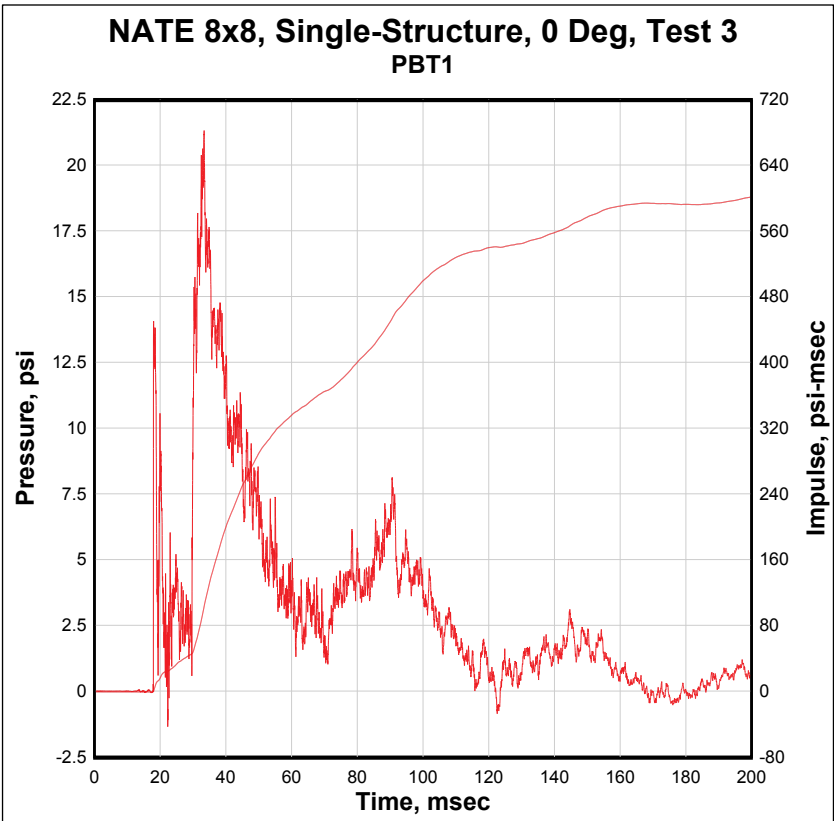
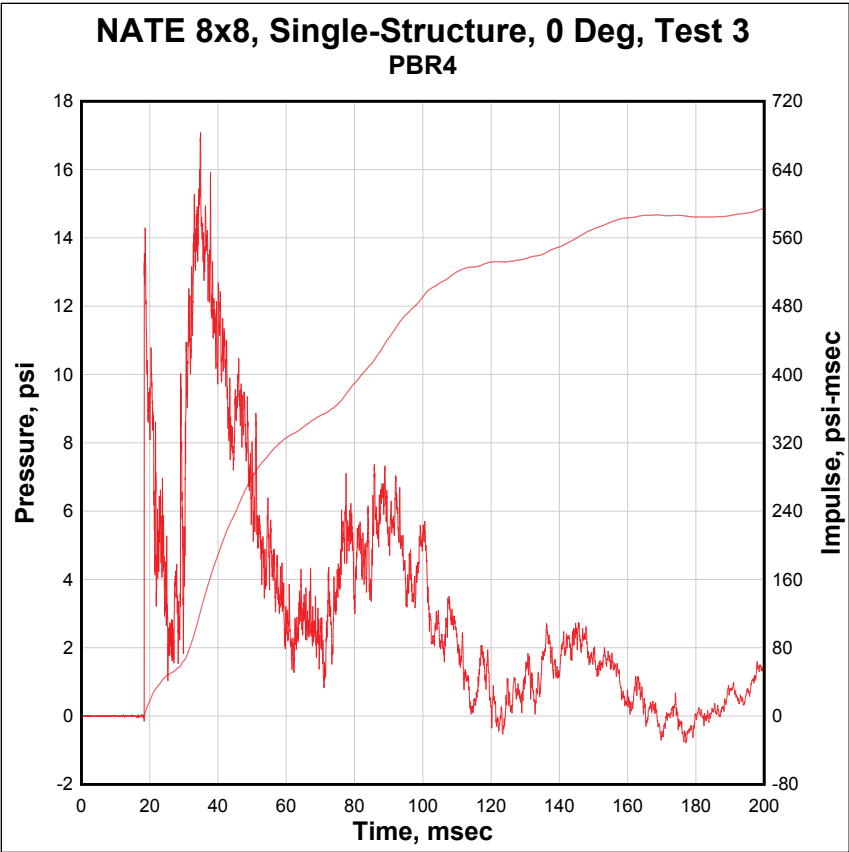


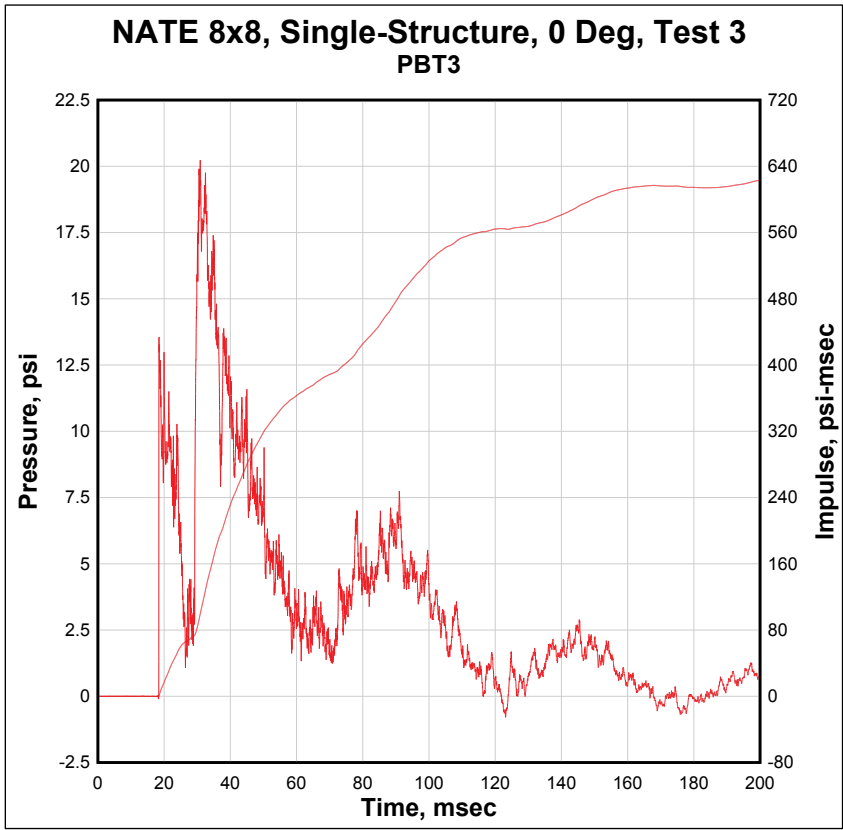
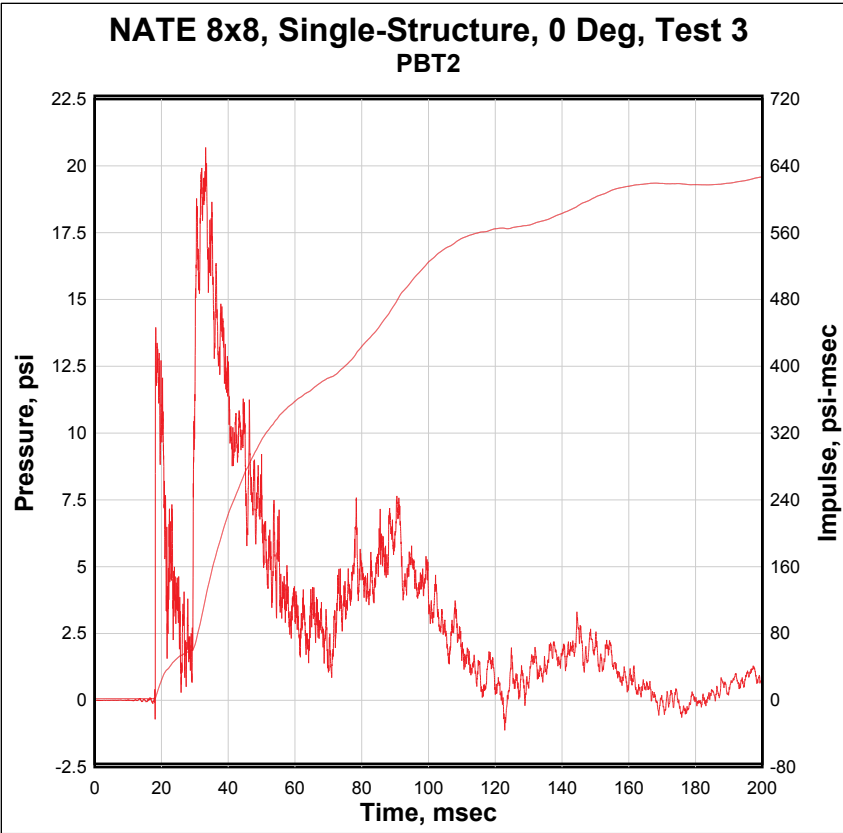


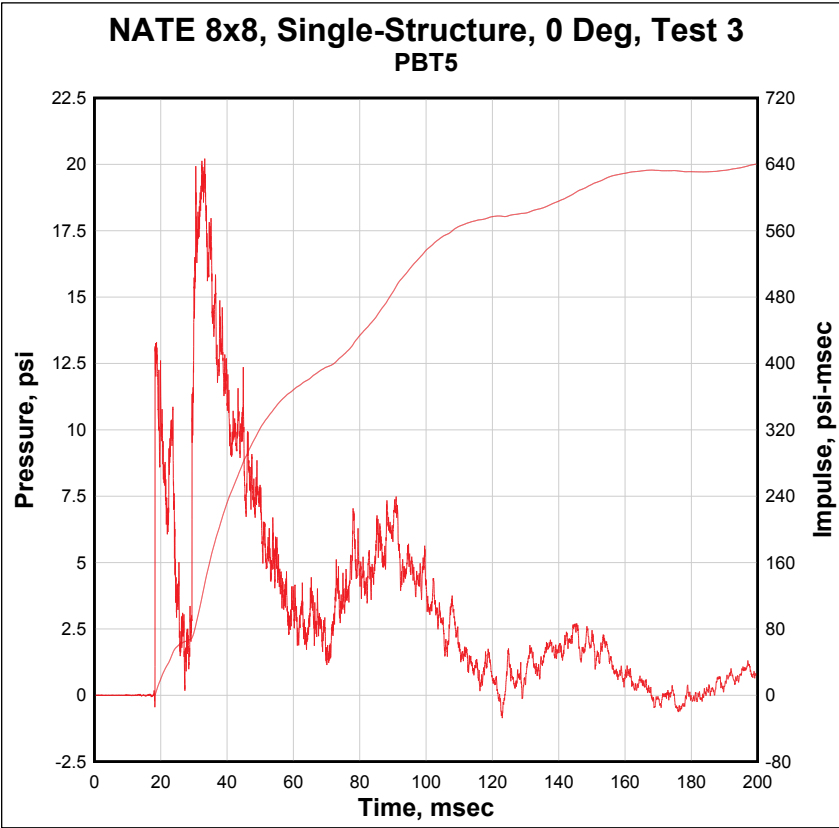
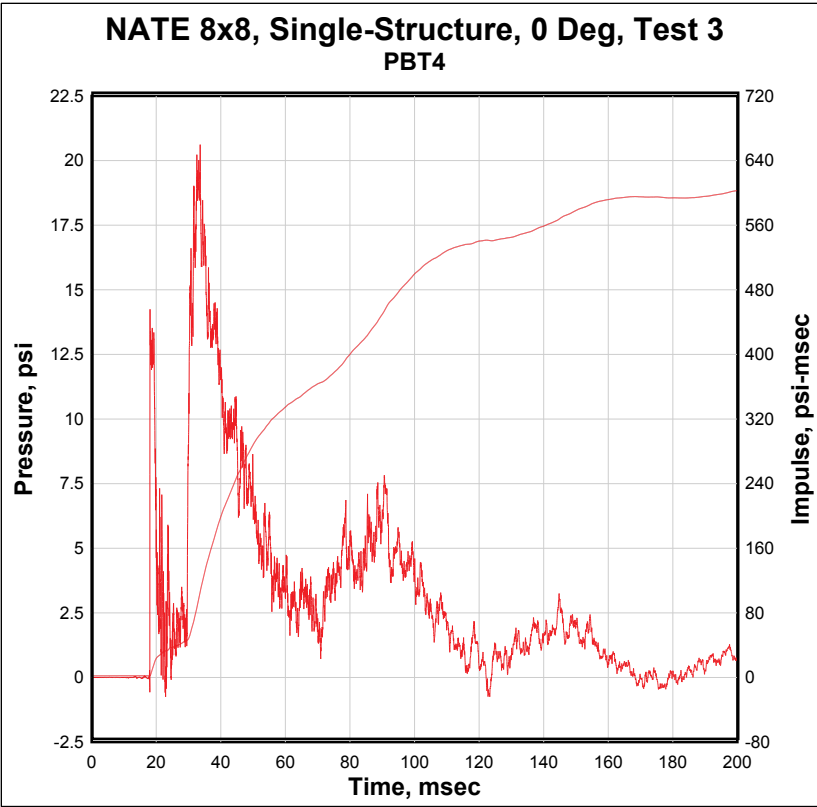


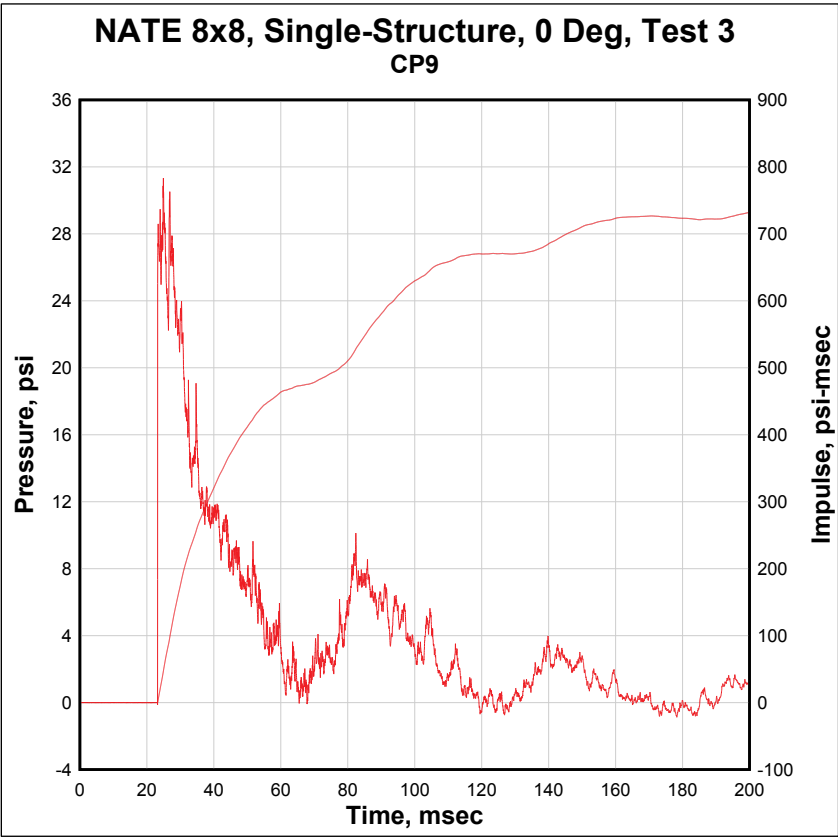
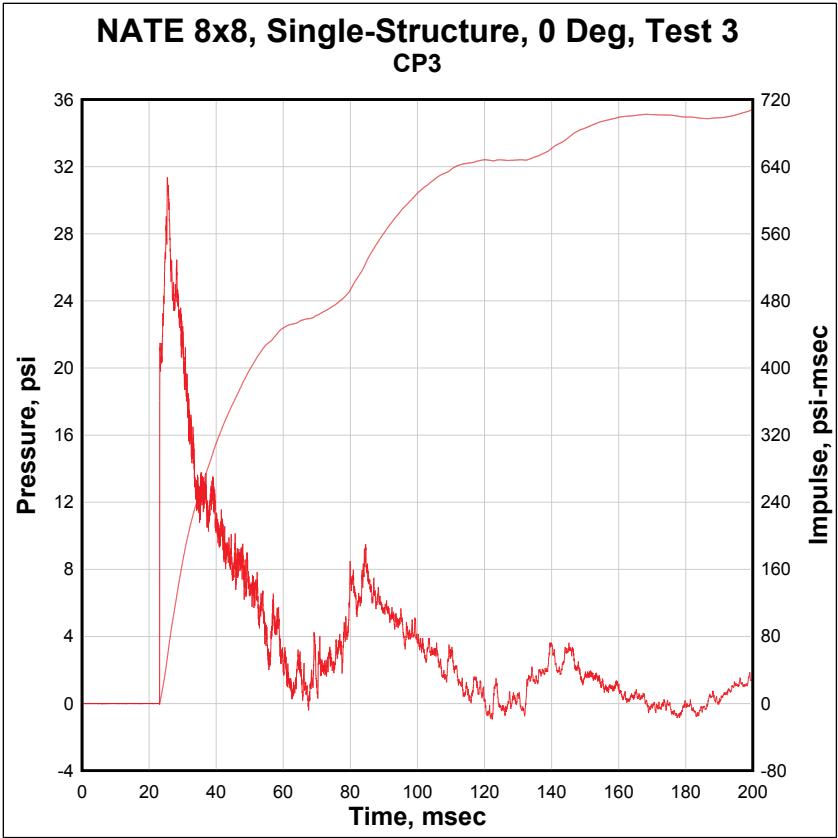




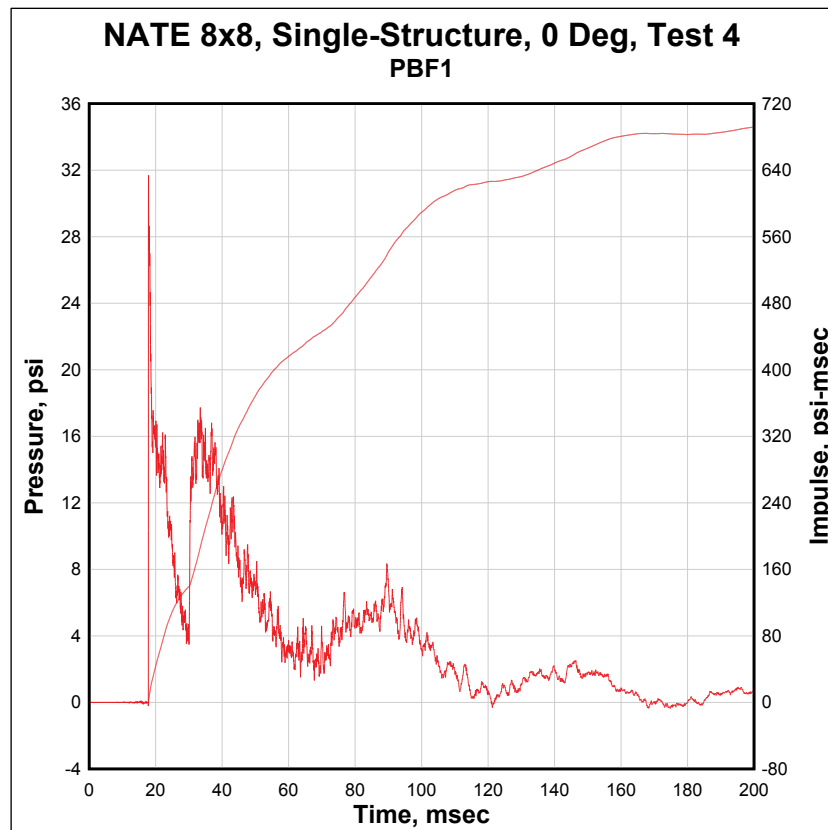


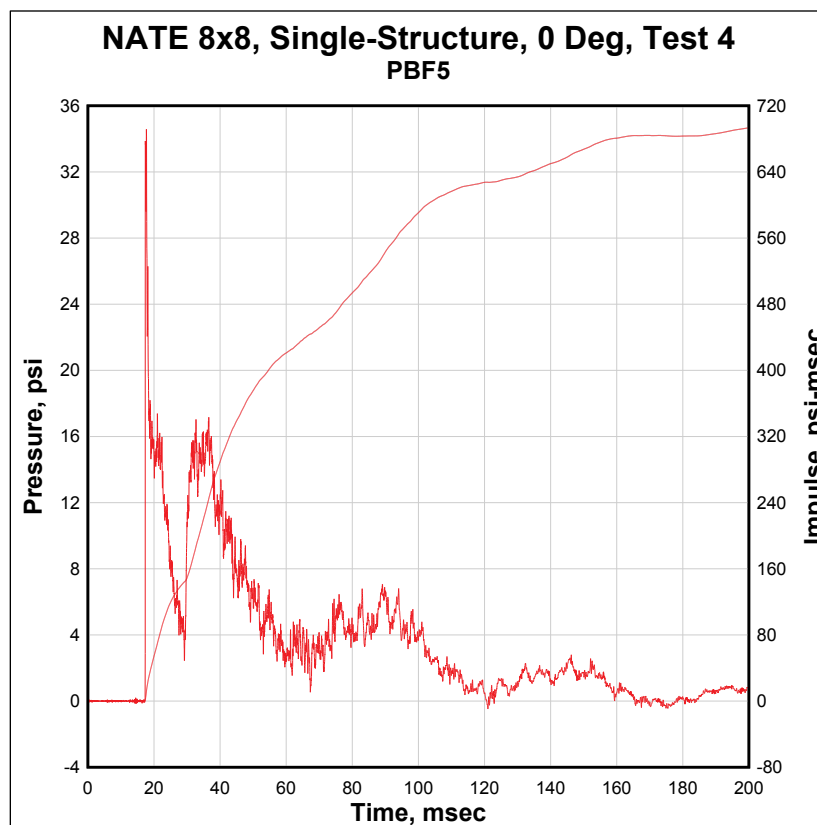
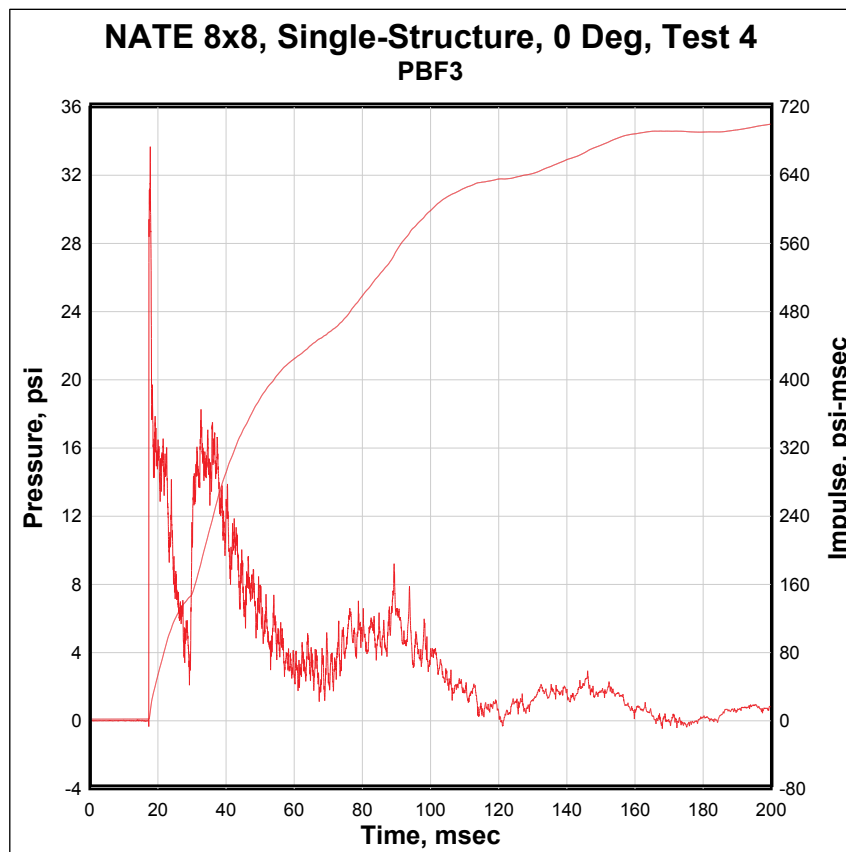


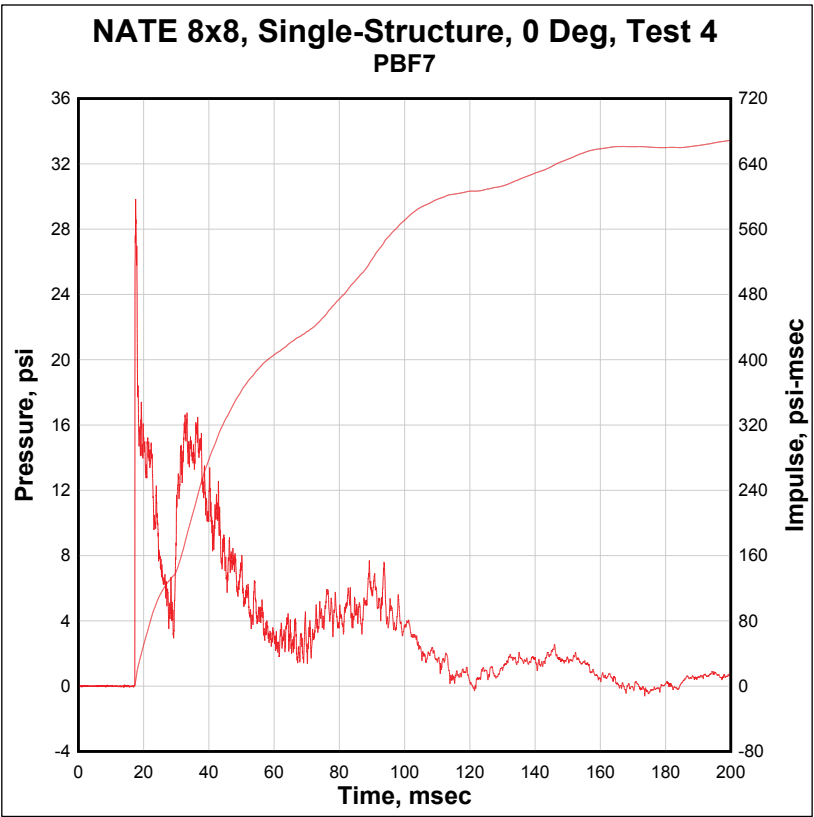
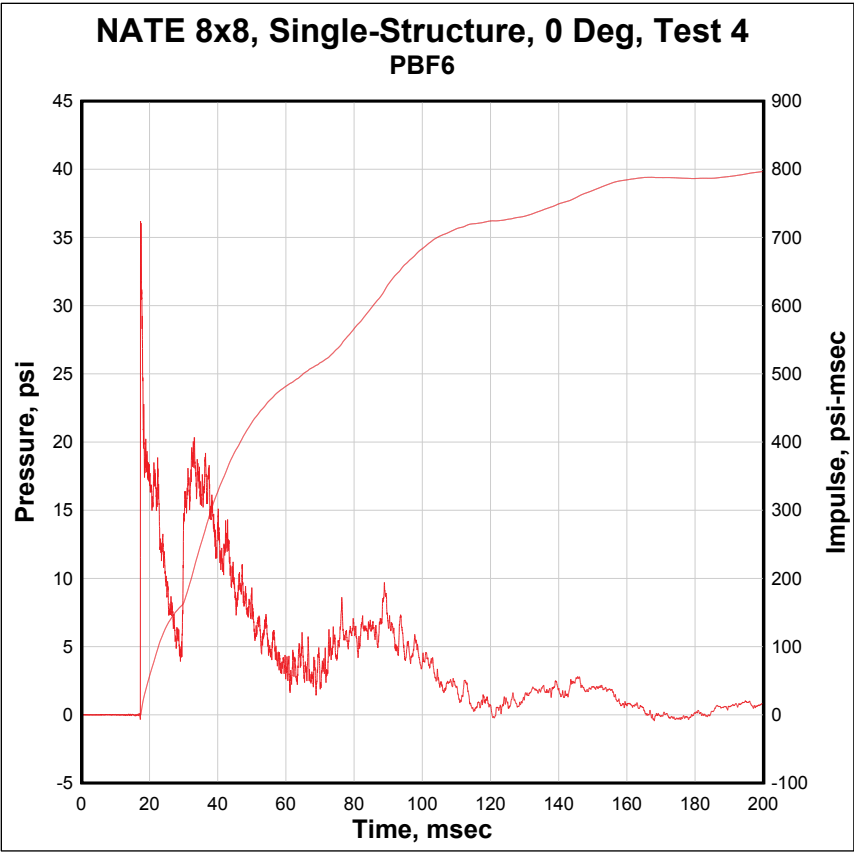


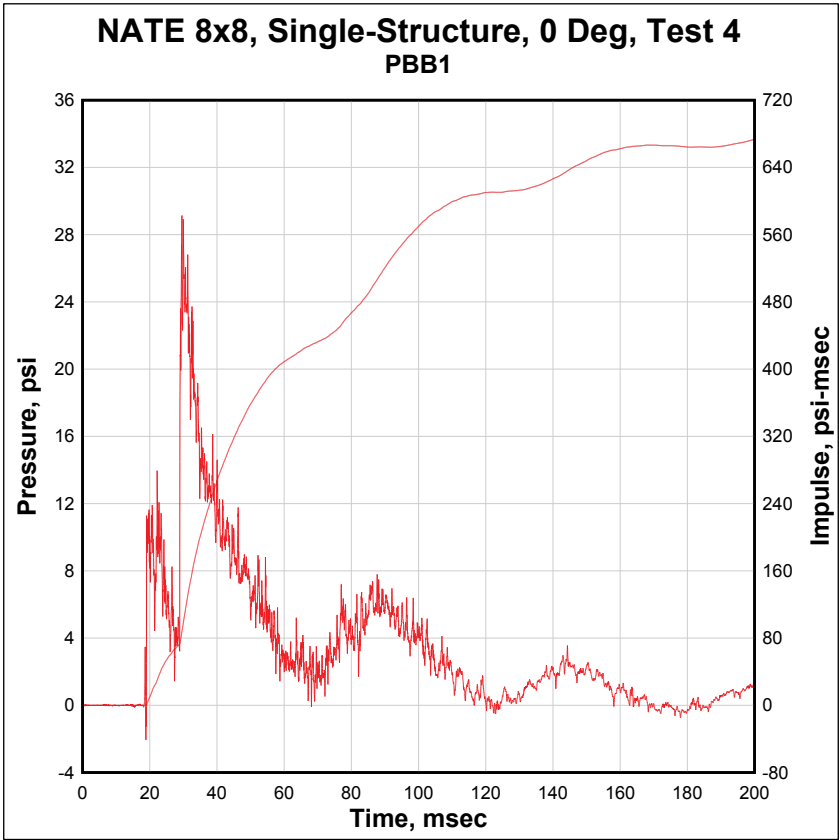
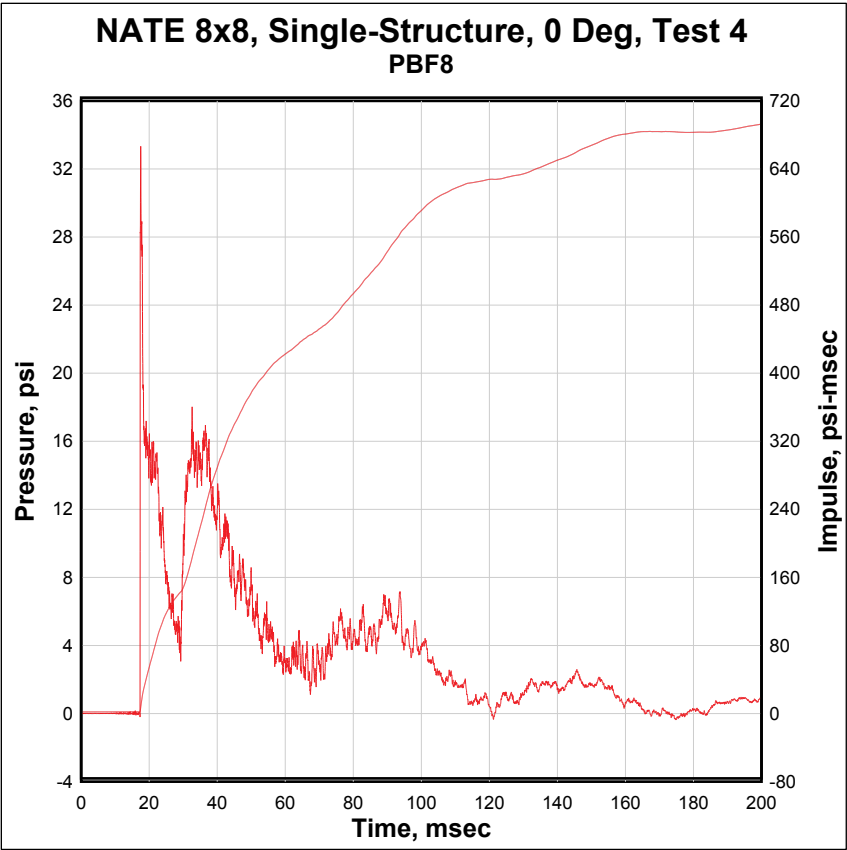


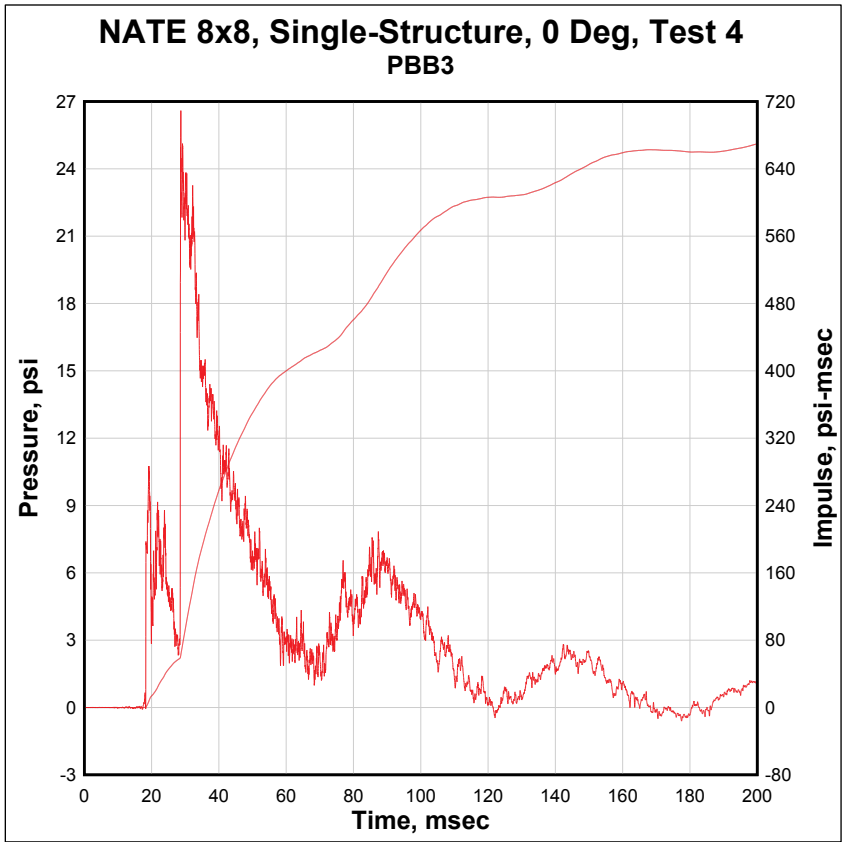
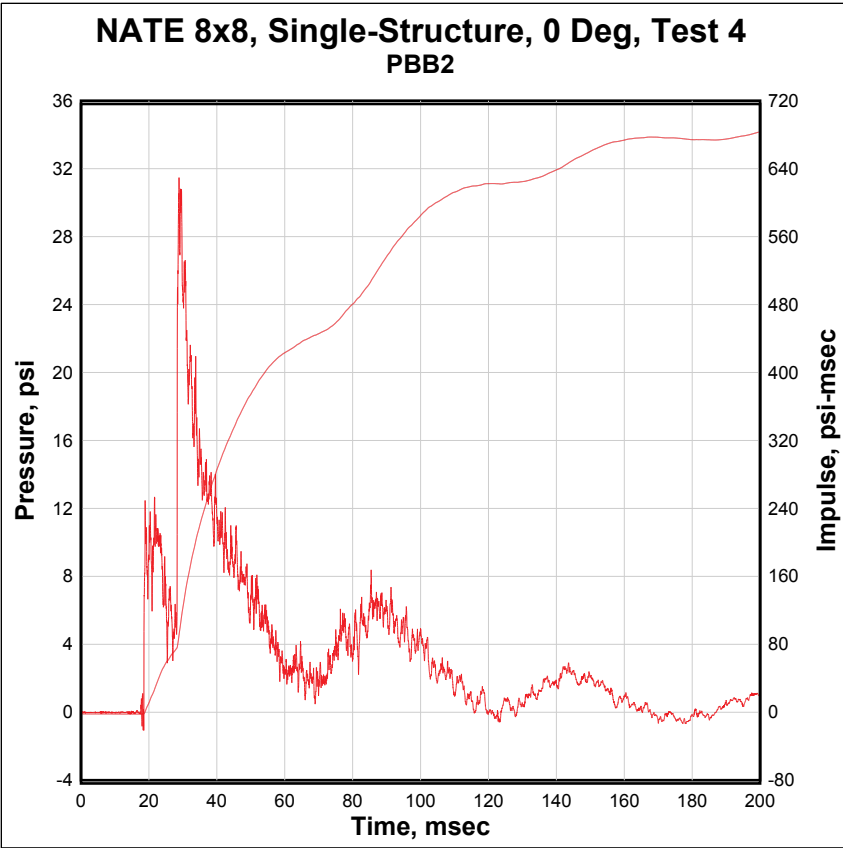
Appendix D: Pressure and Impulse Data from Test 4

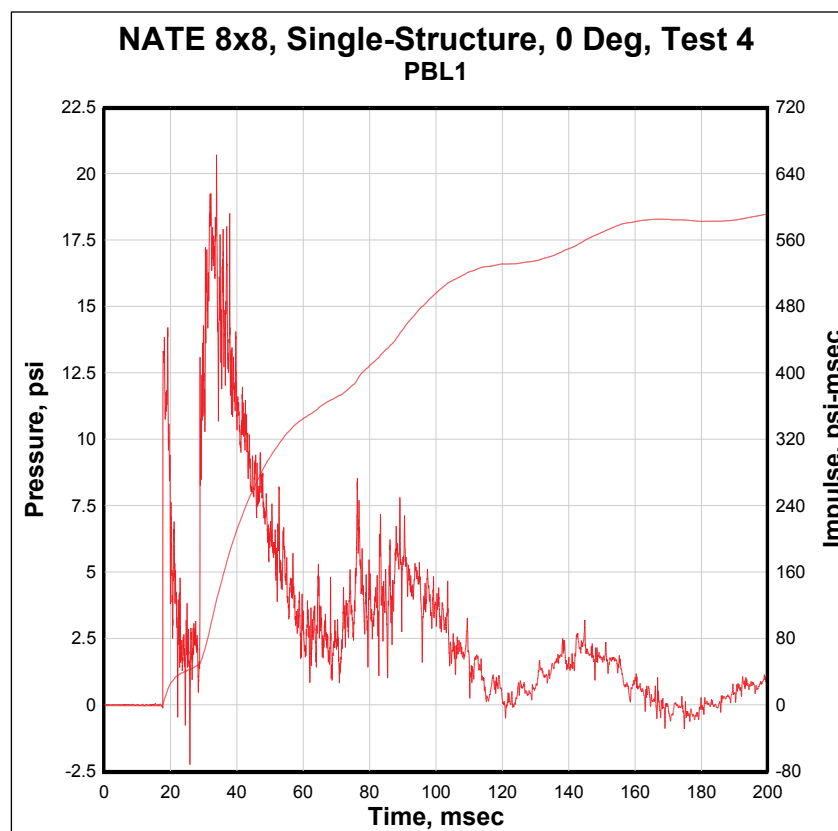
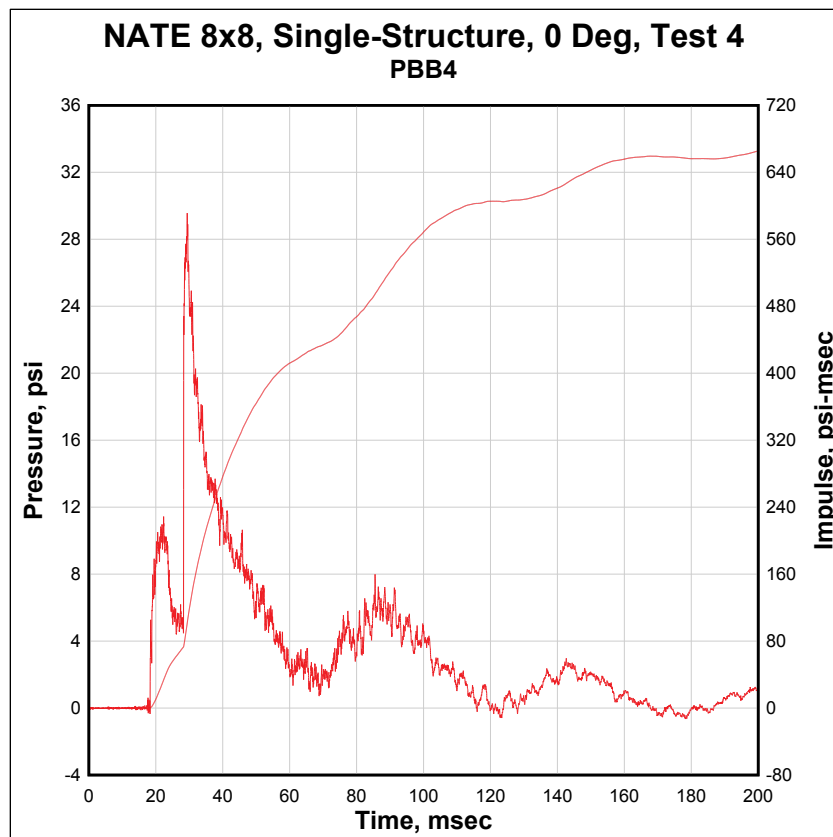


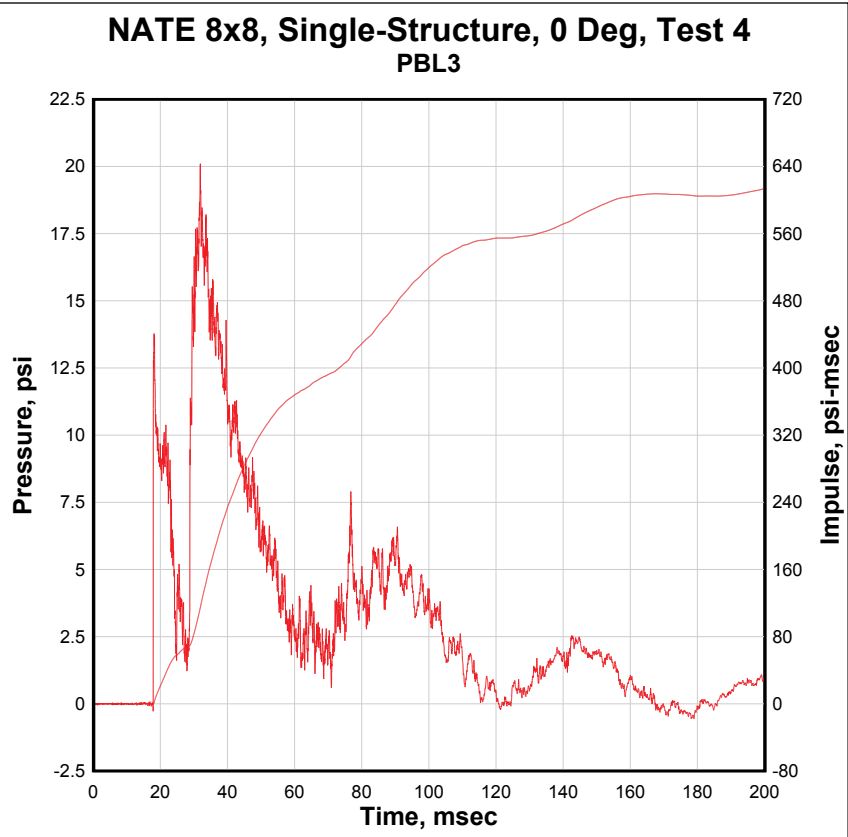
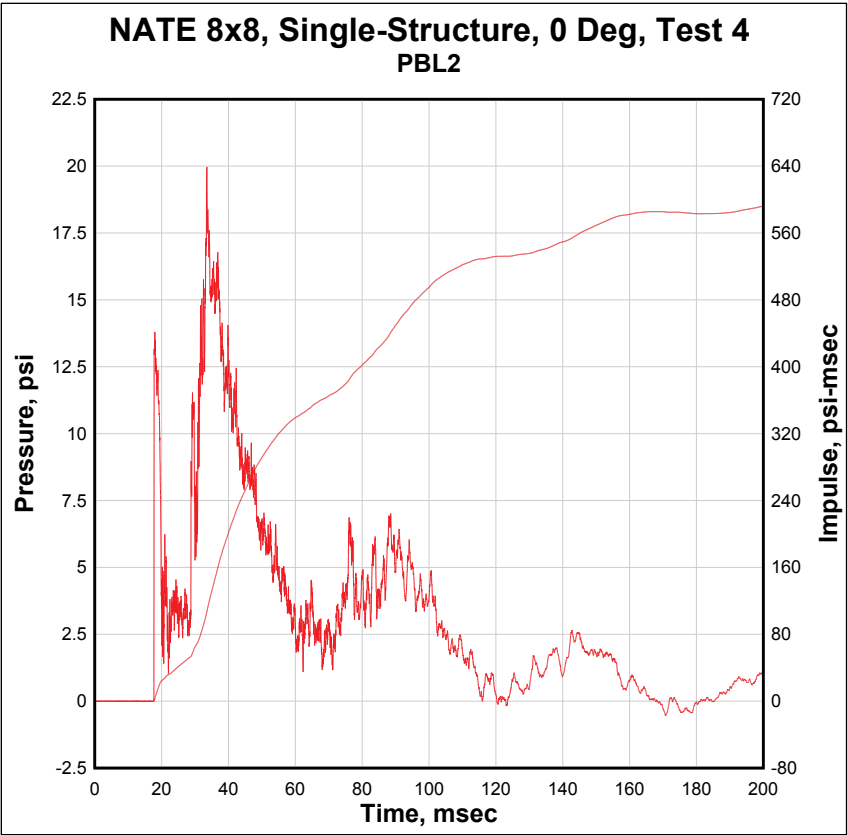


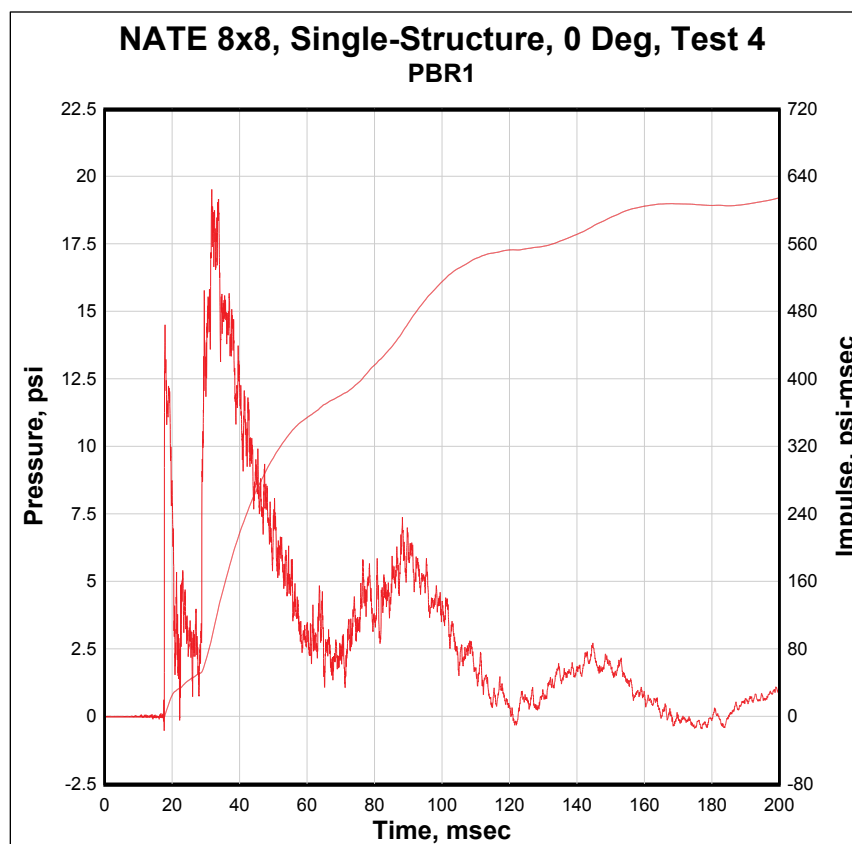
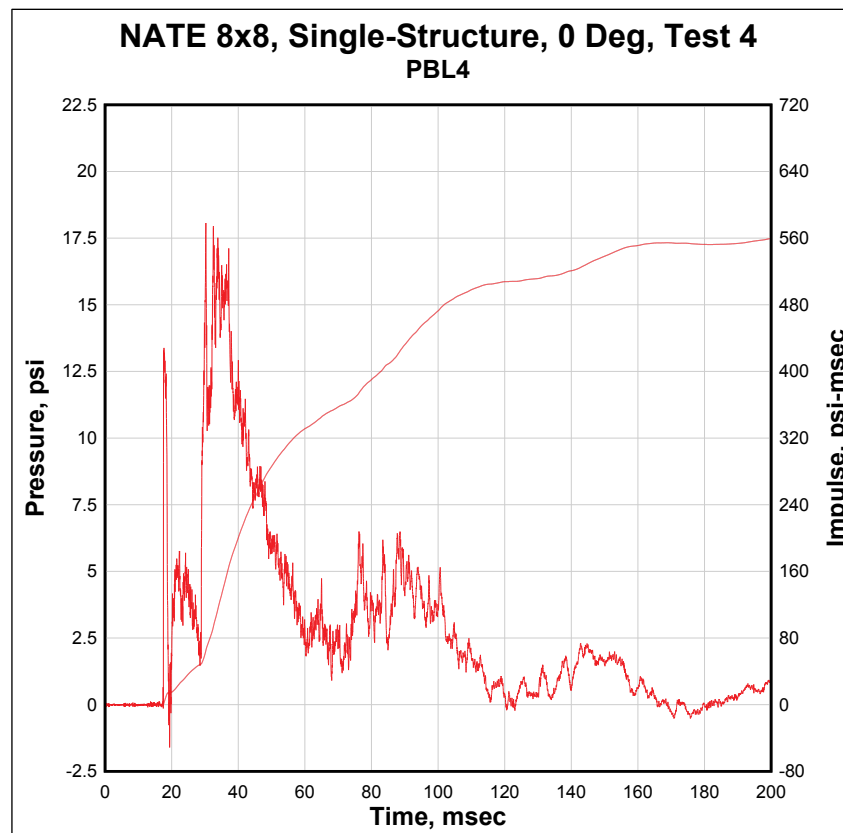


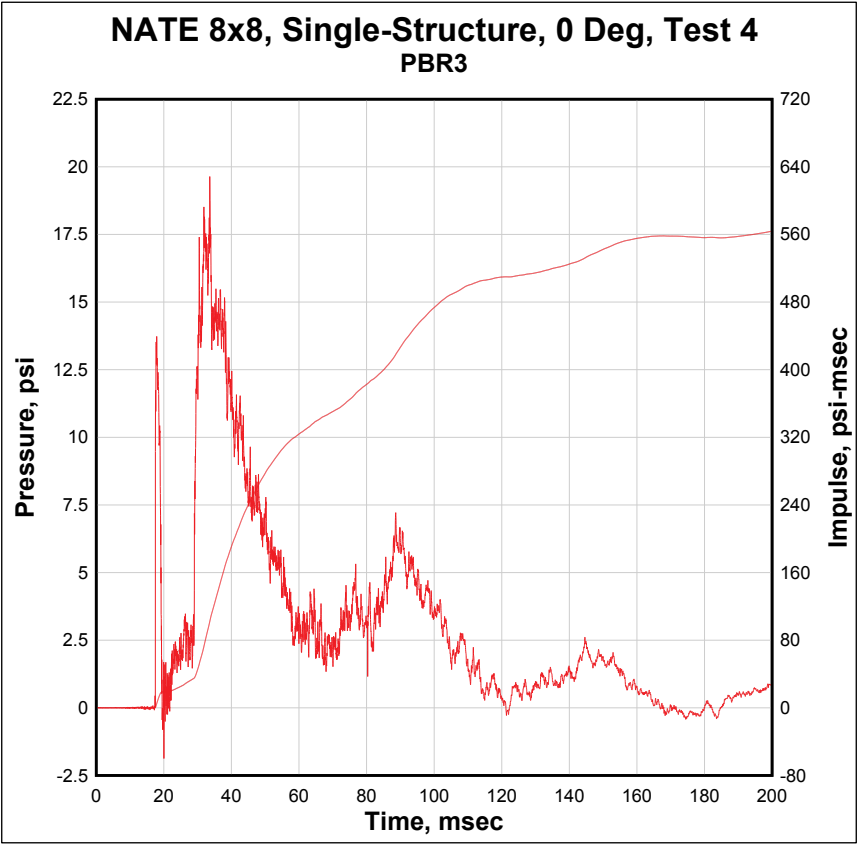
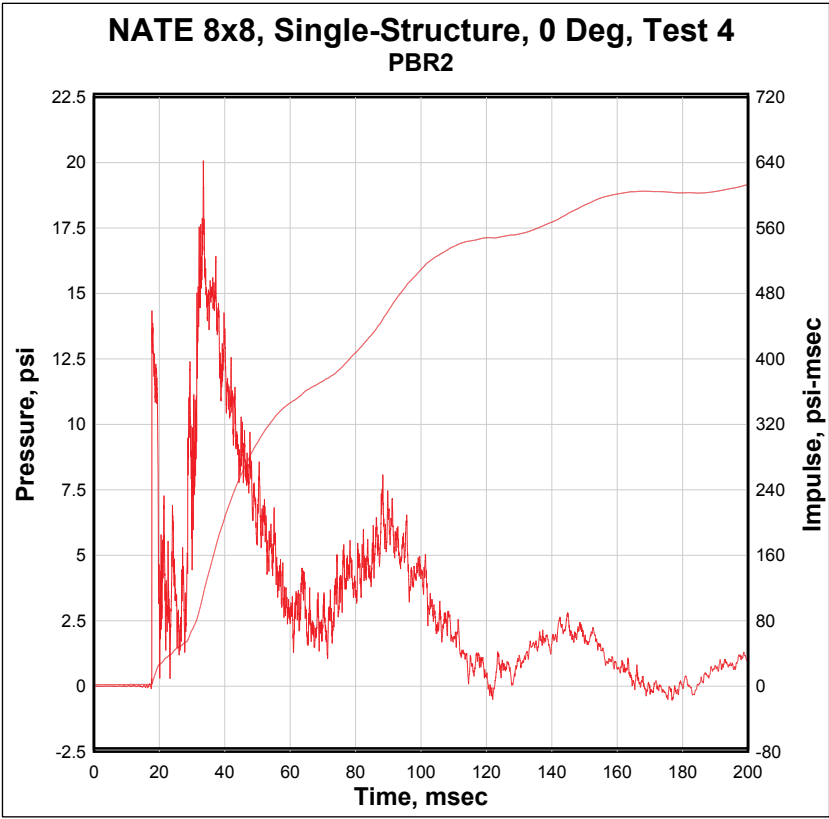


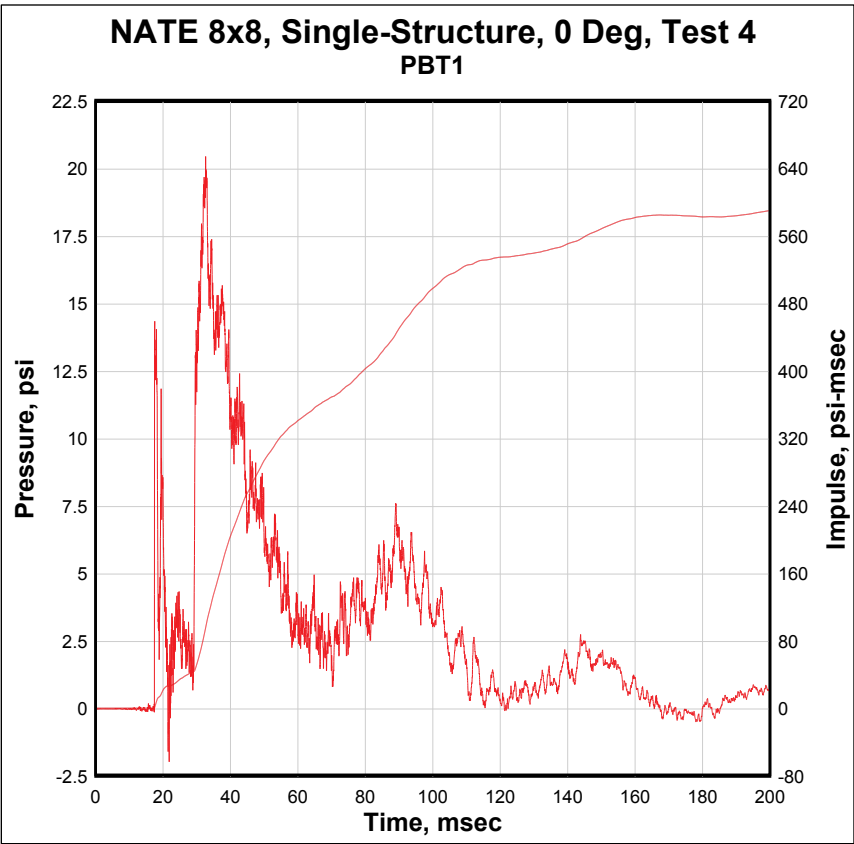
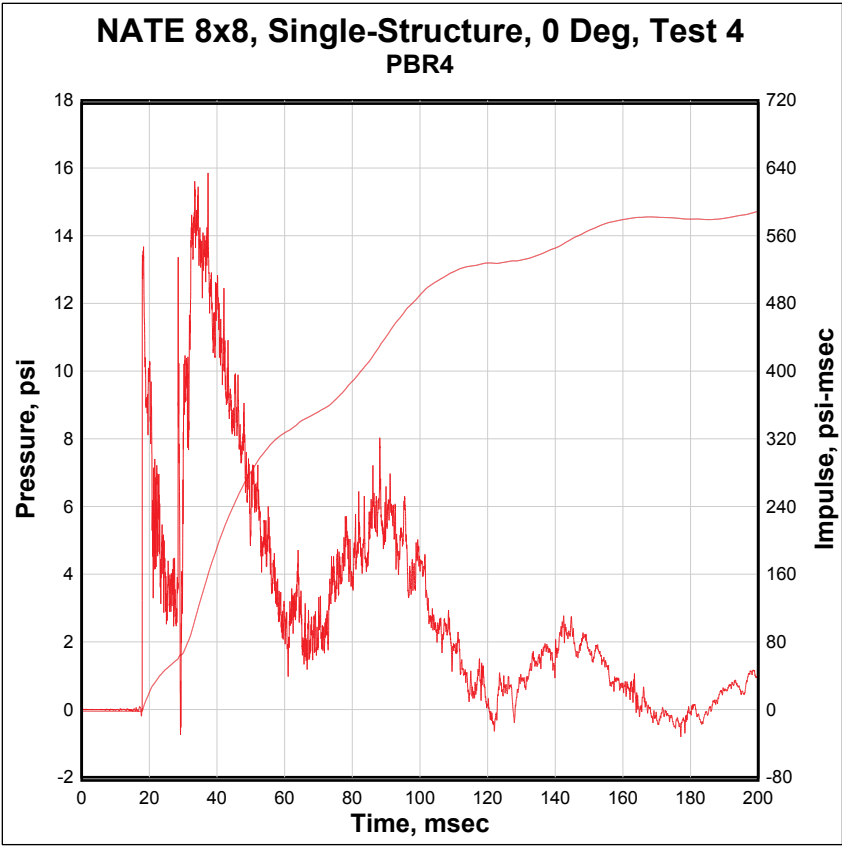


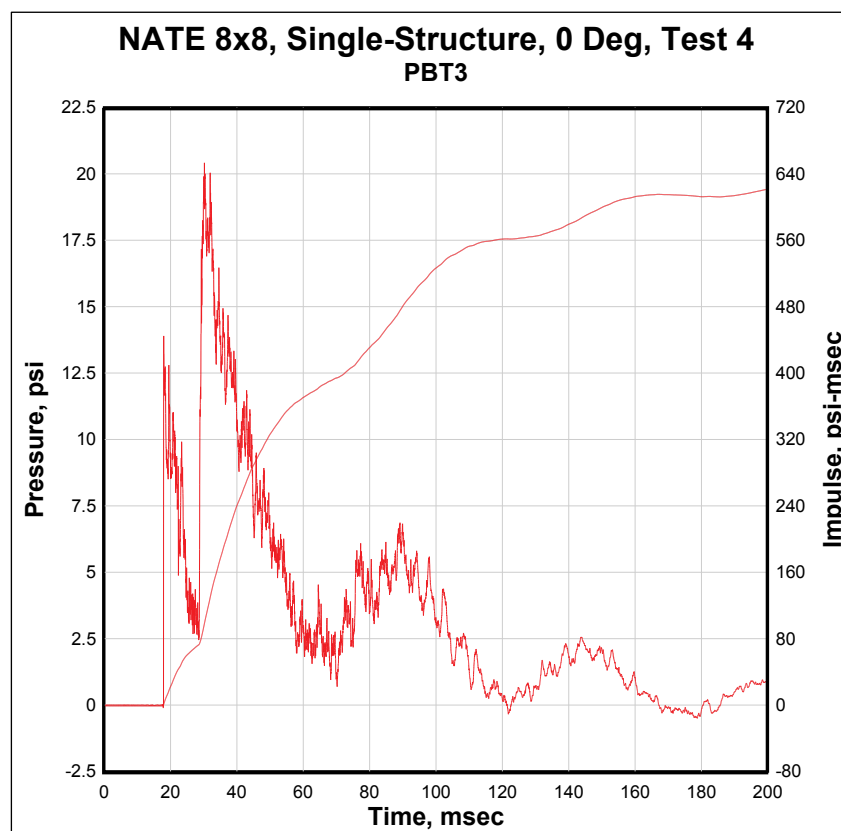
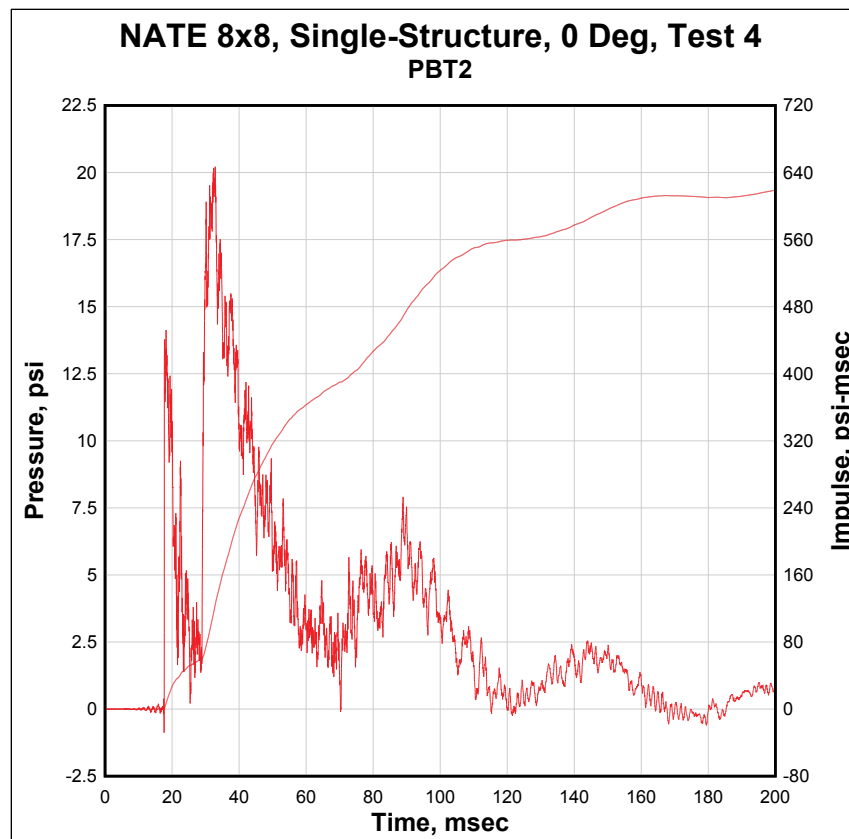


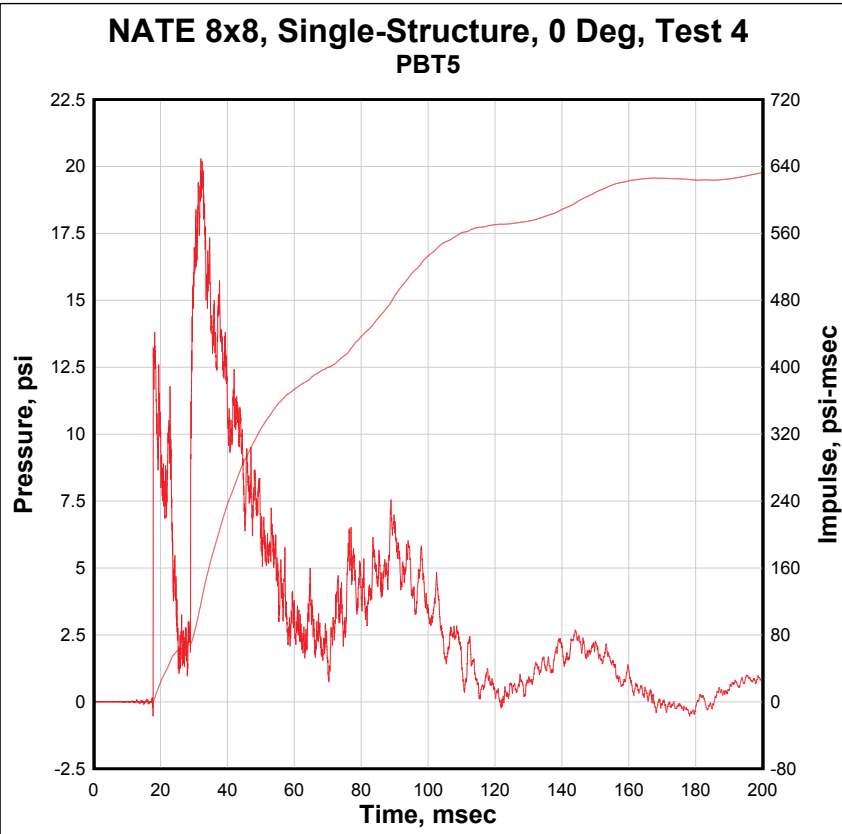
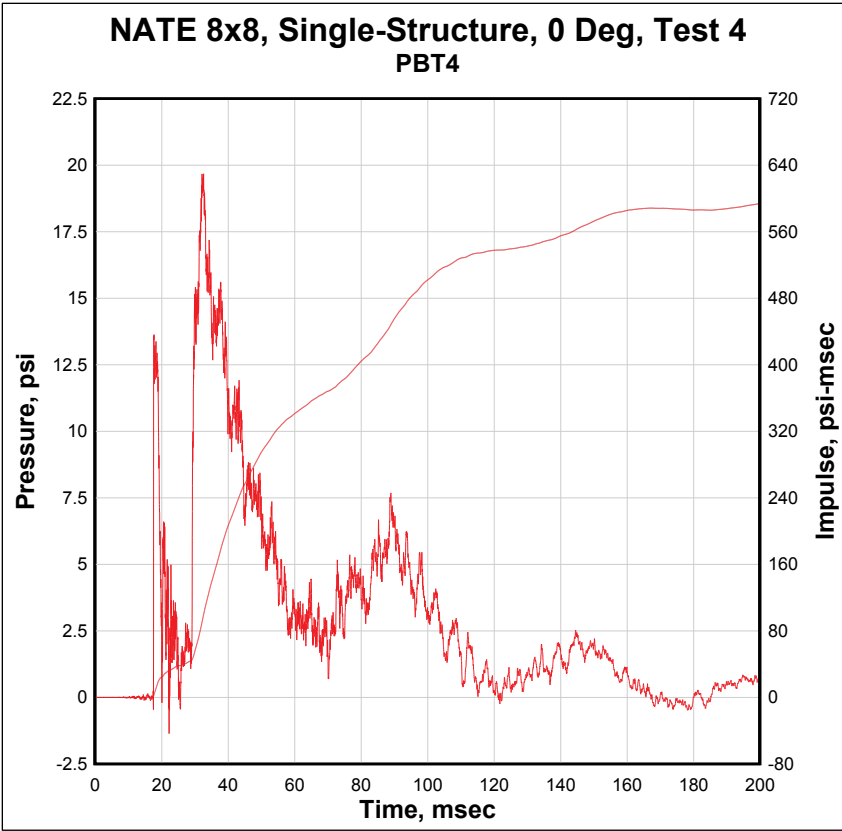


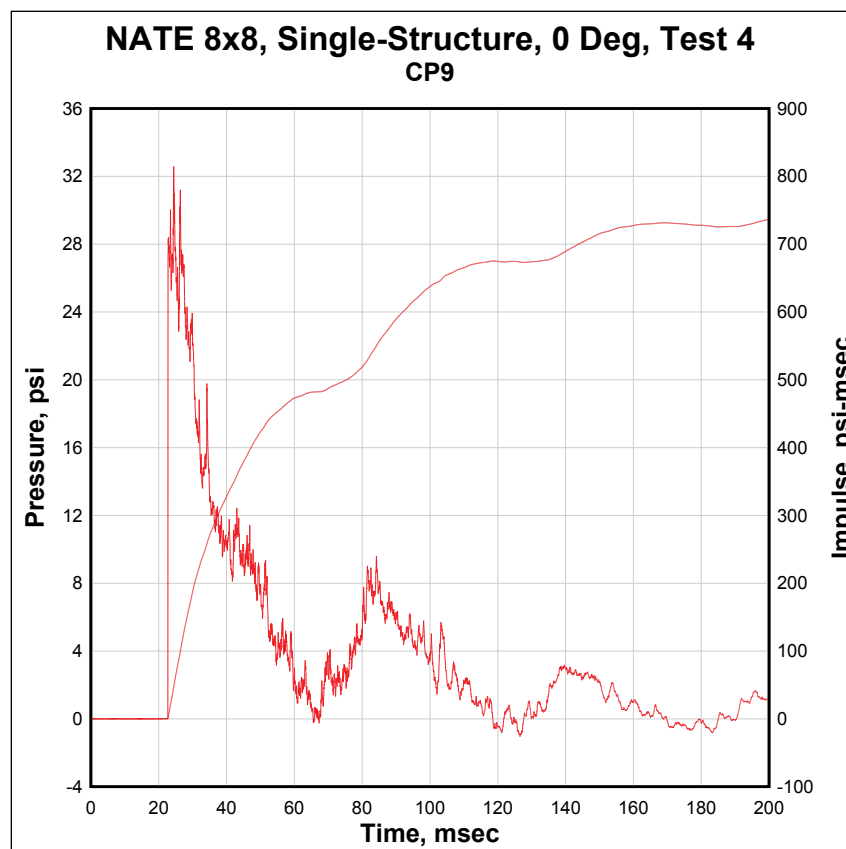
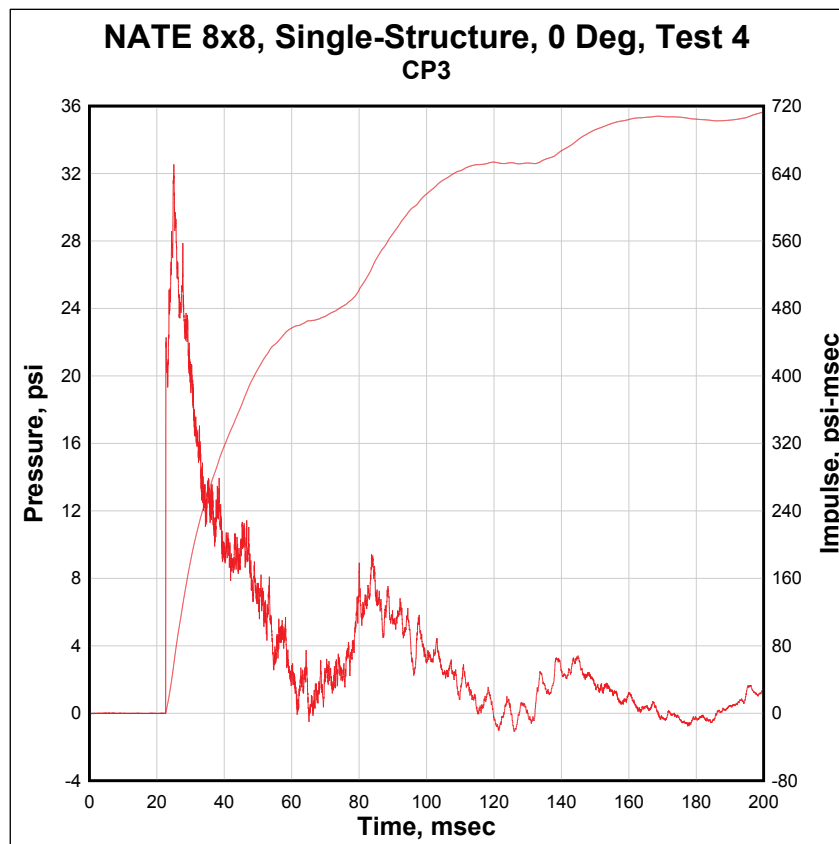




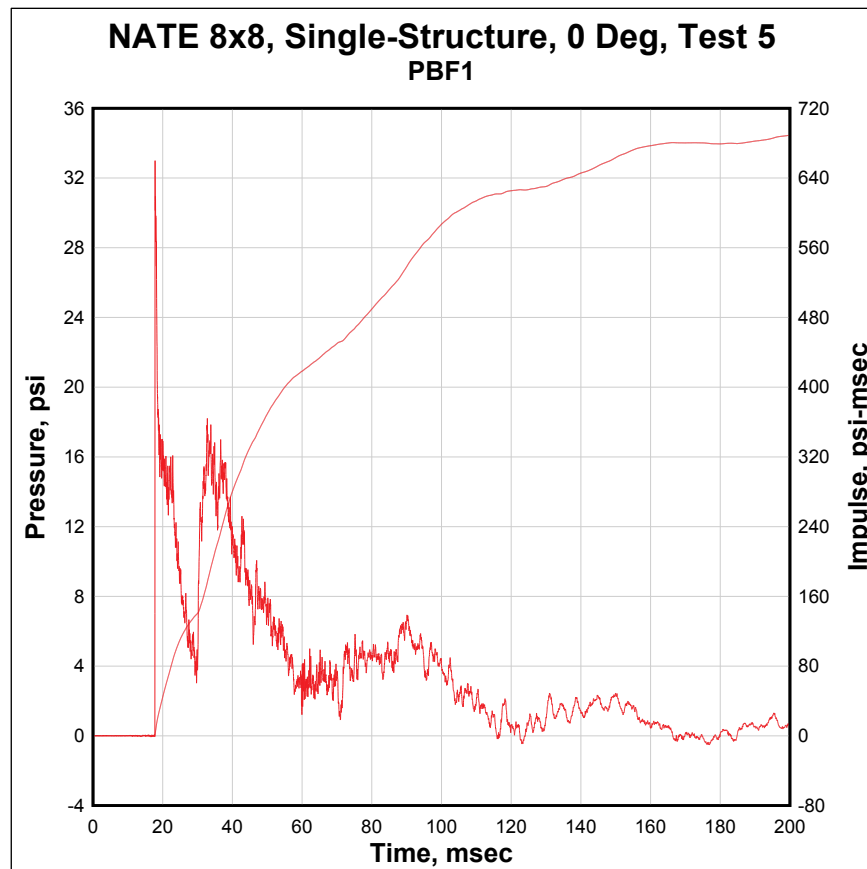


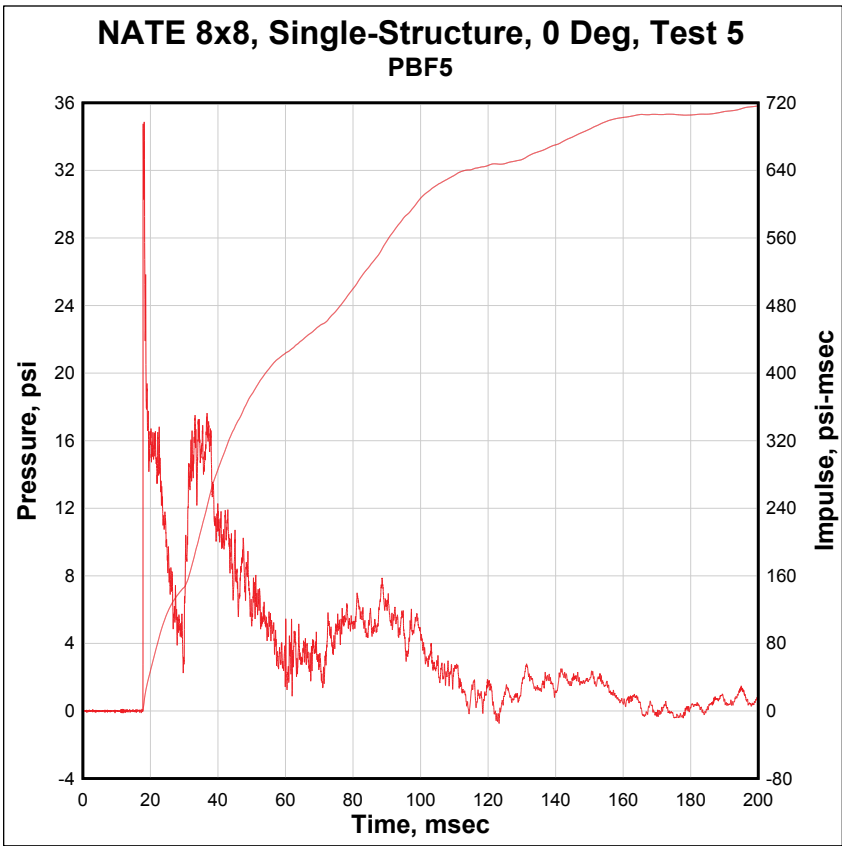
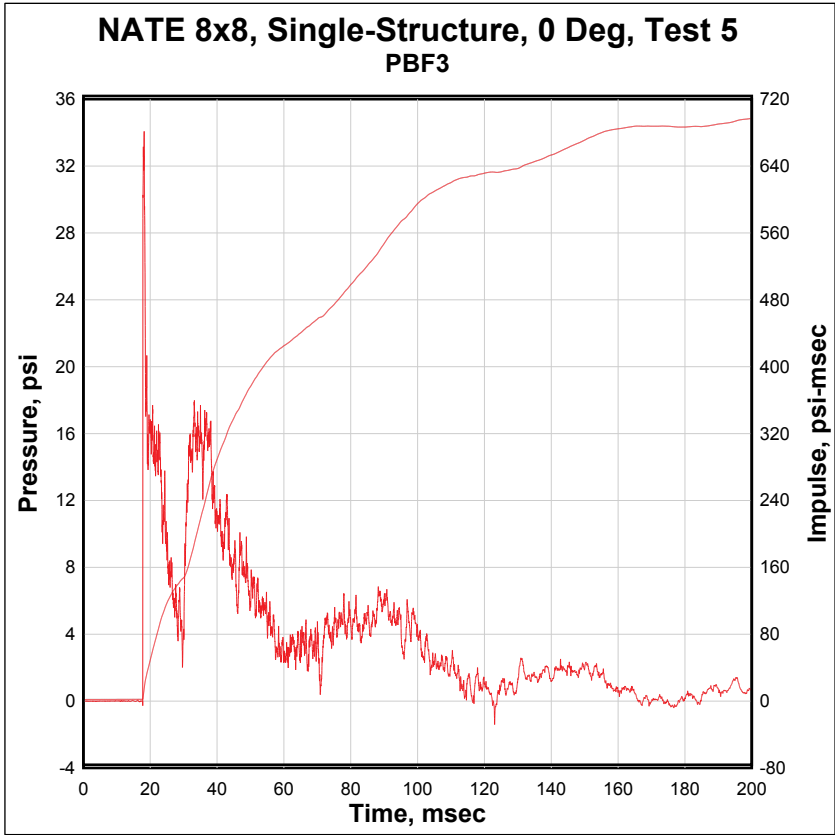


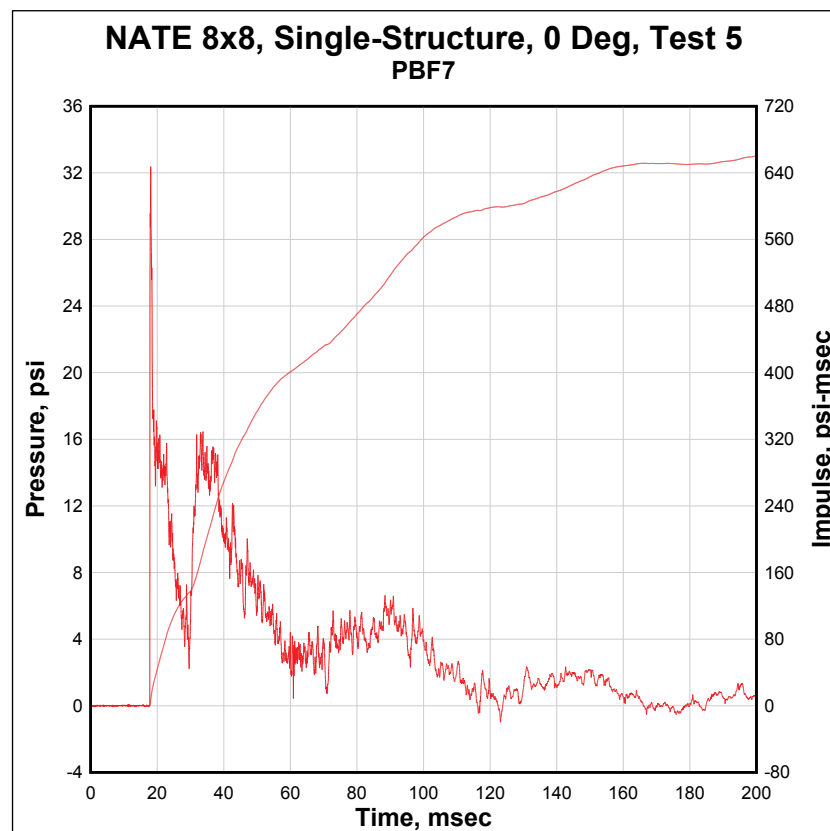
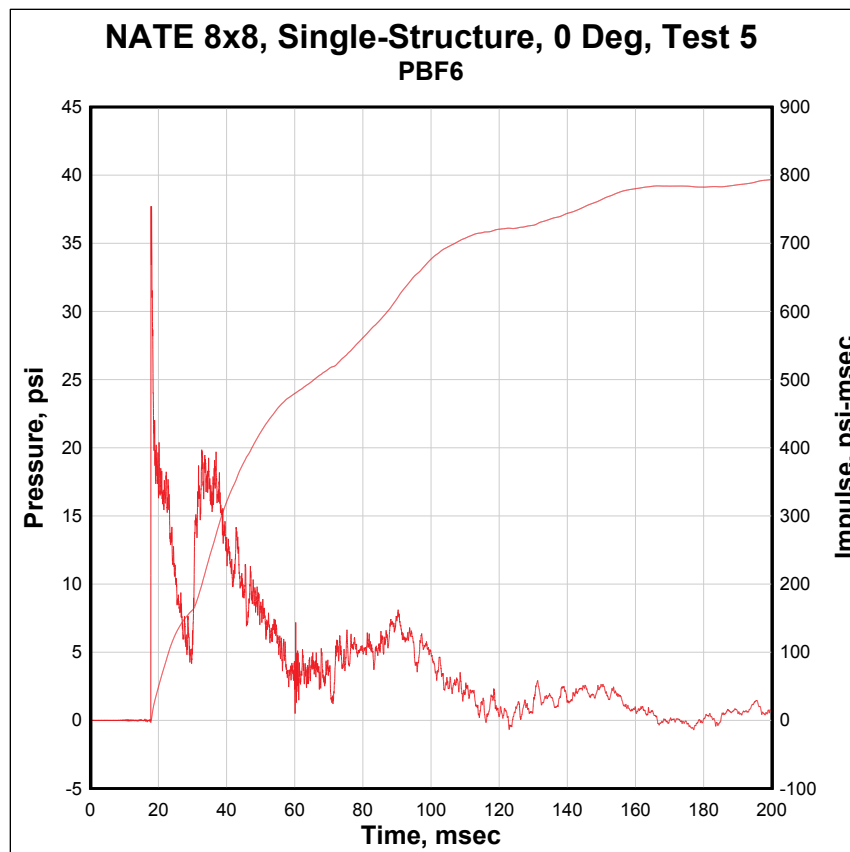


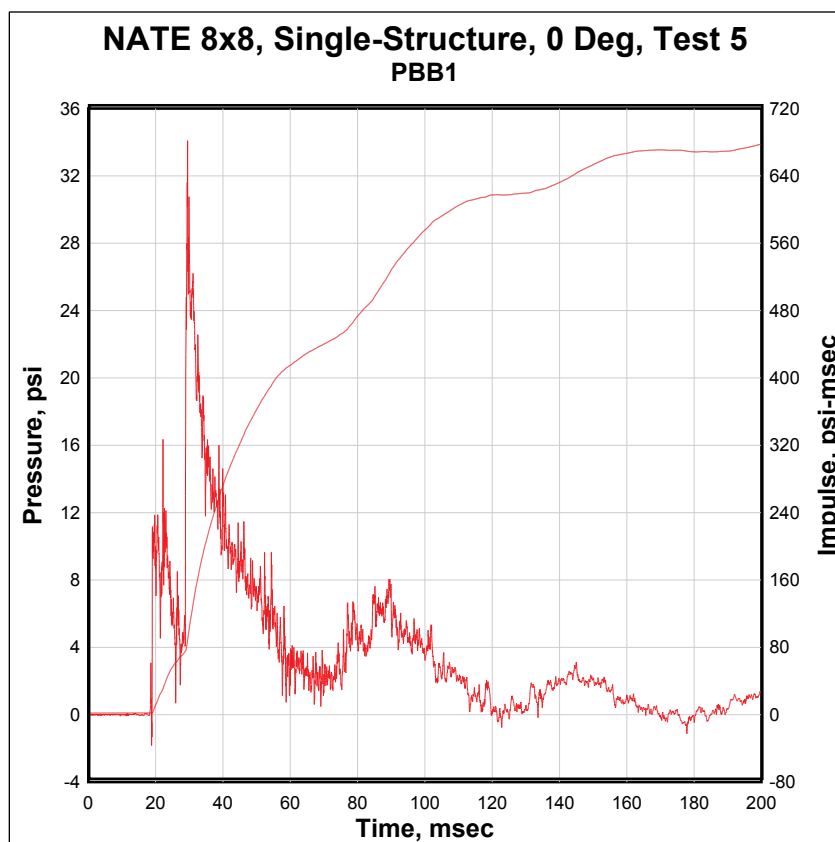
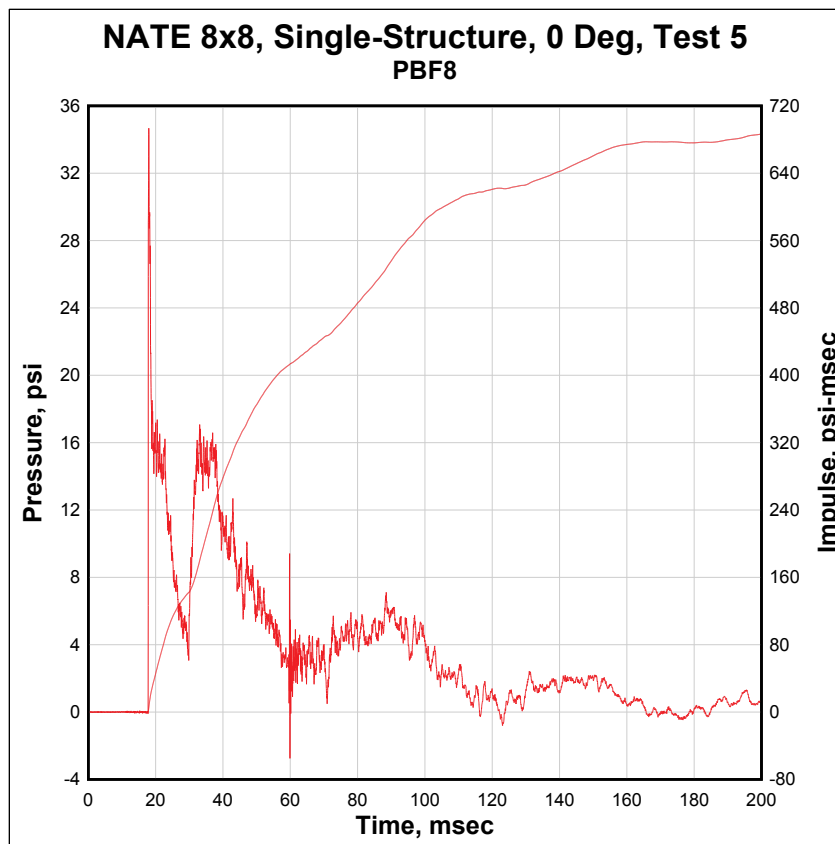


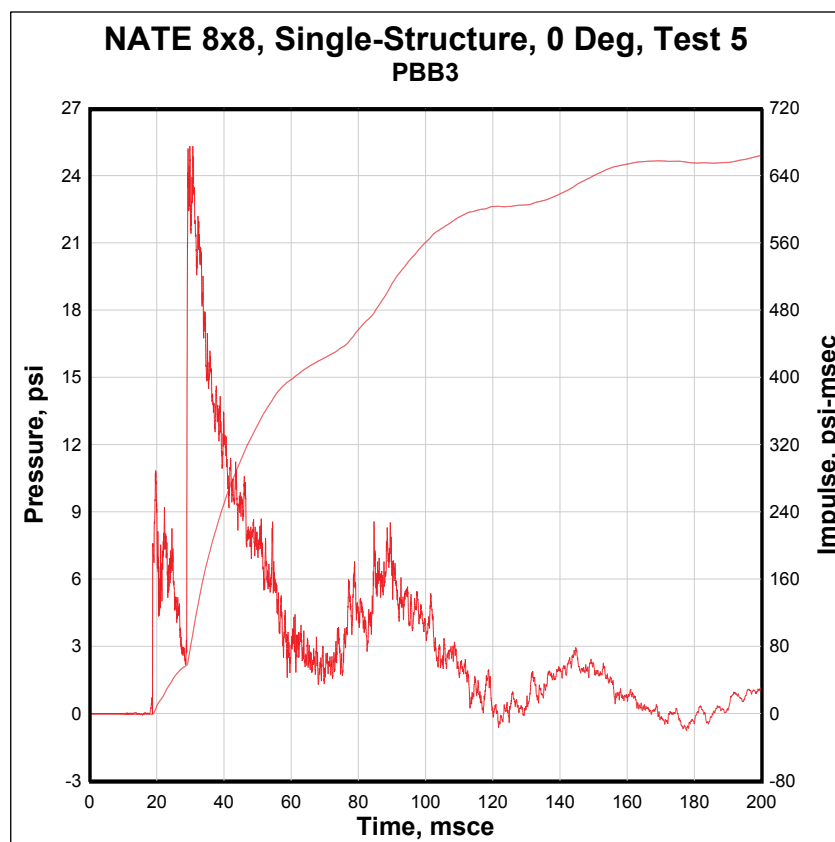
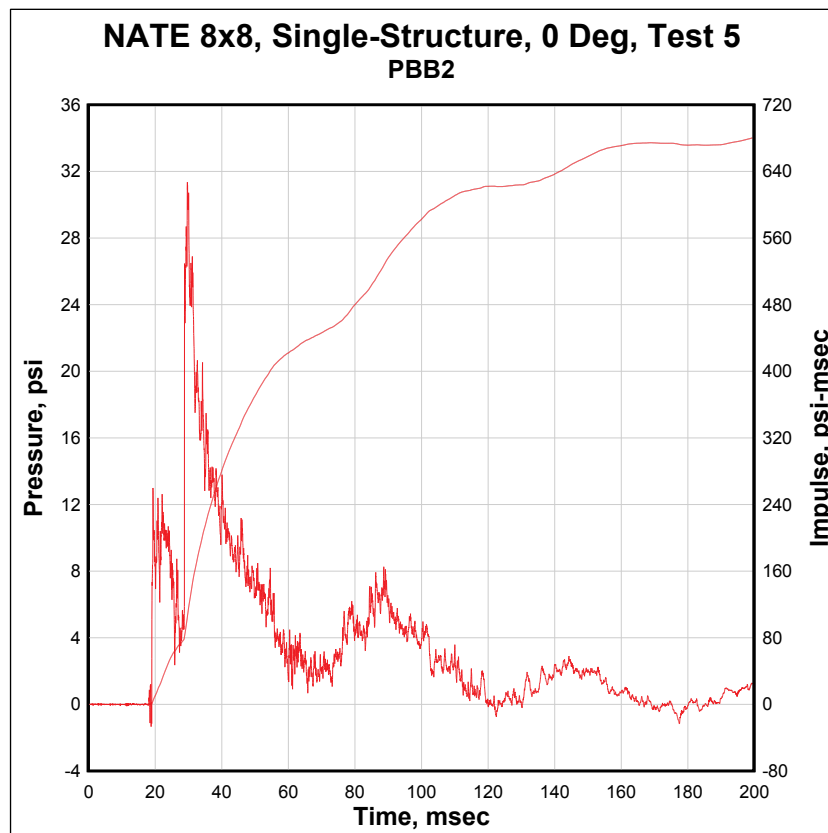
Appendix E: Pressure and Impulse Data from Test 5

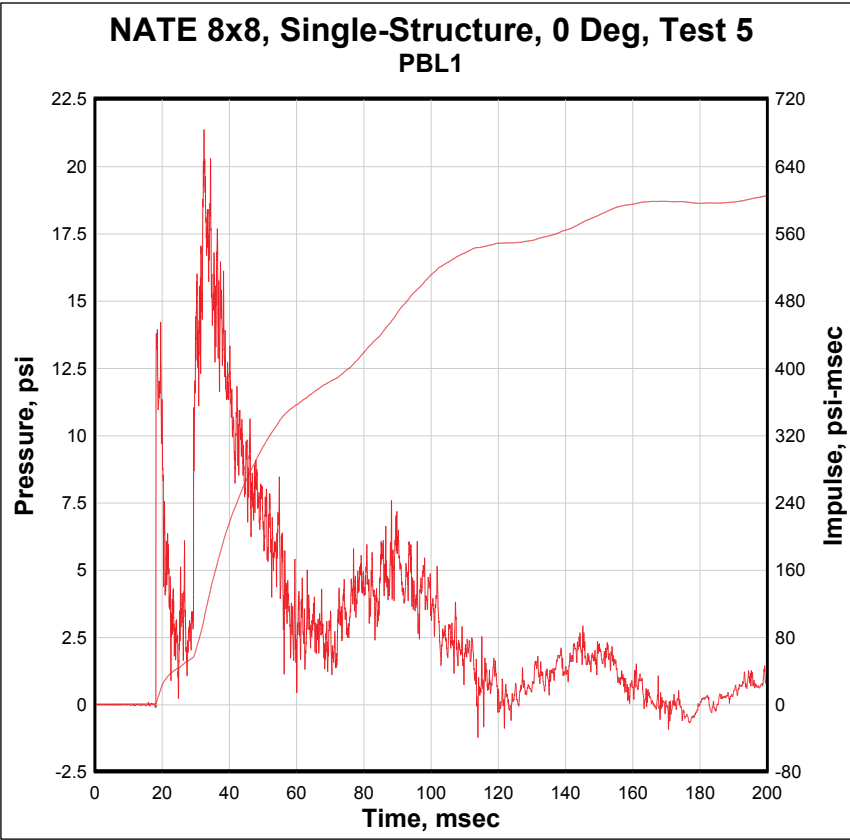
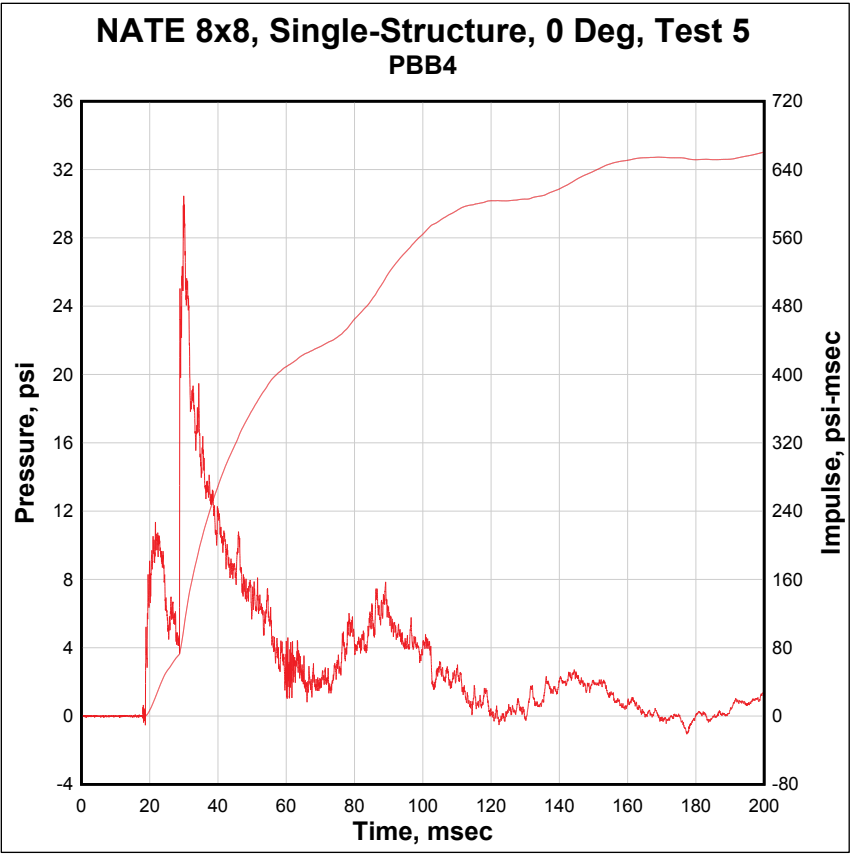


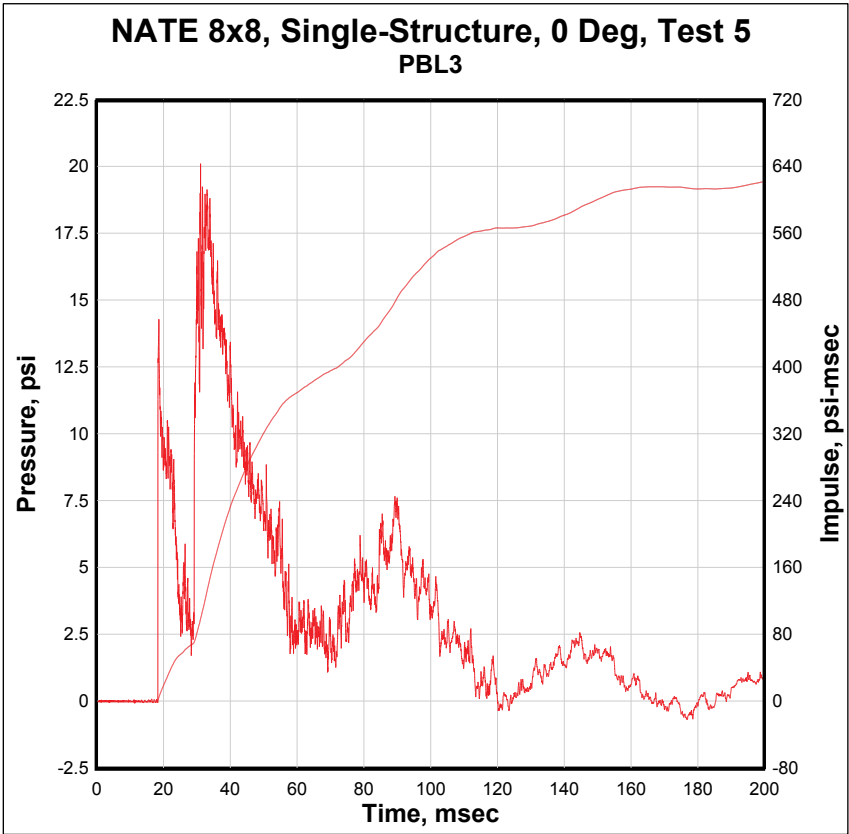
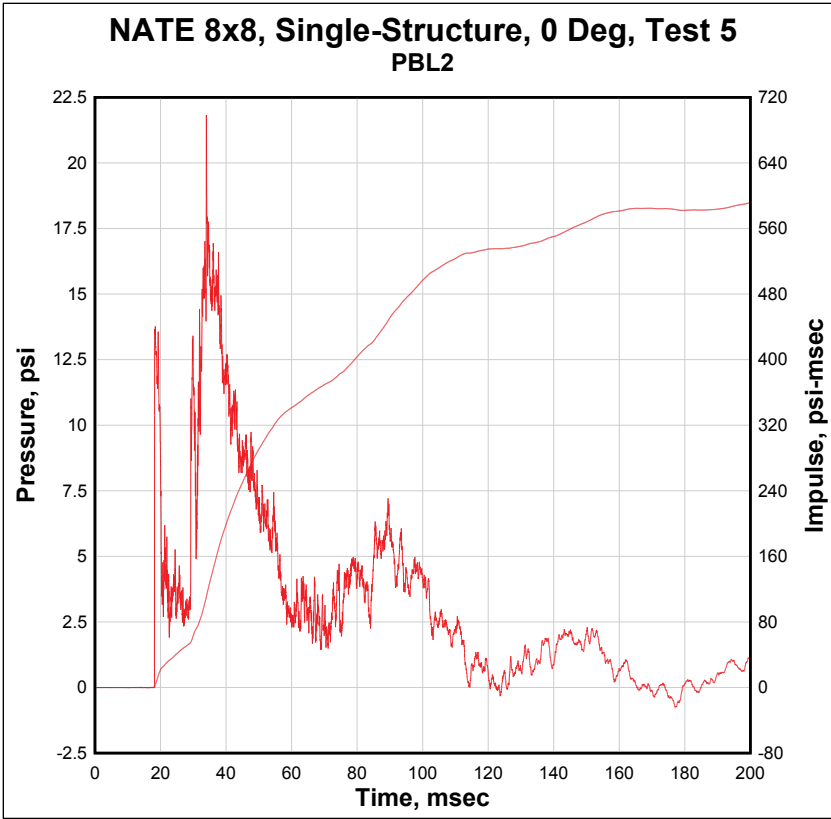


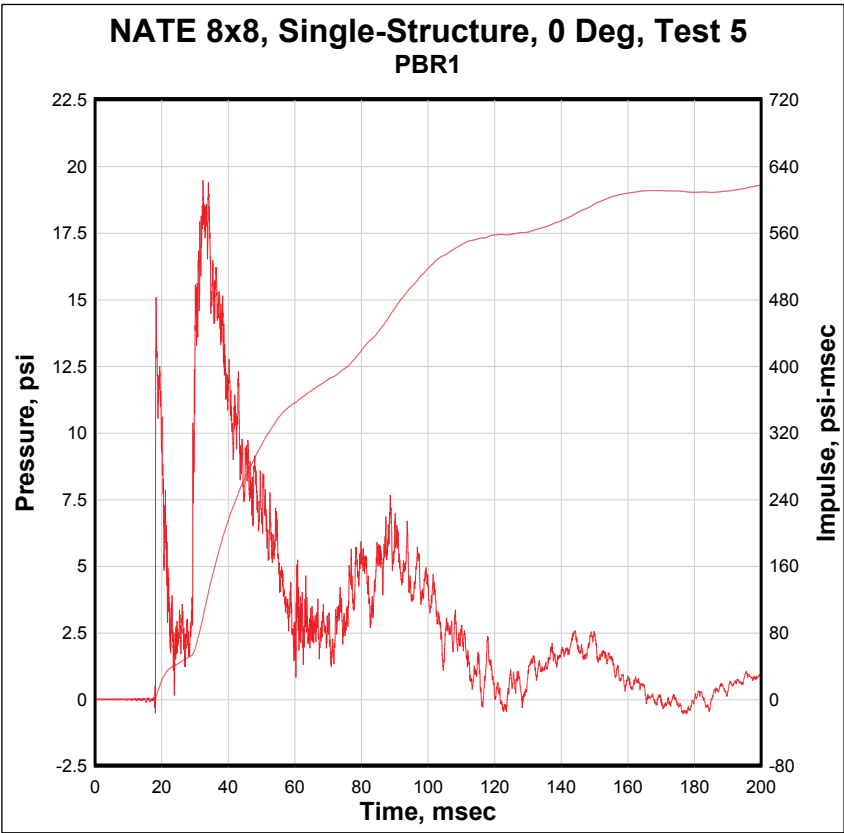
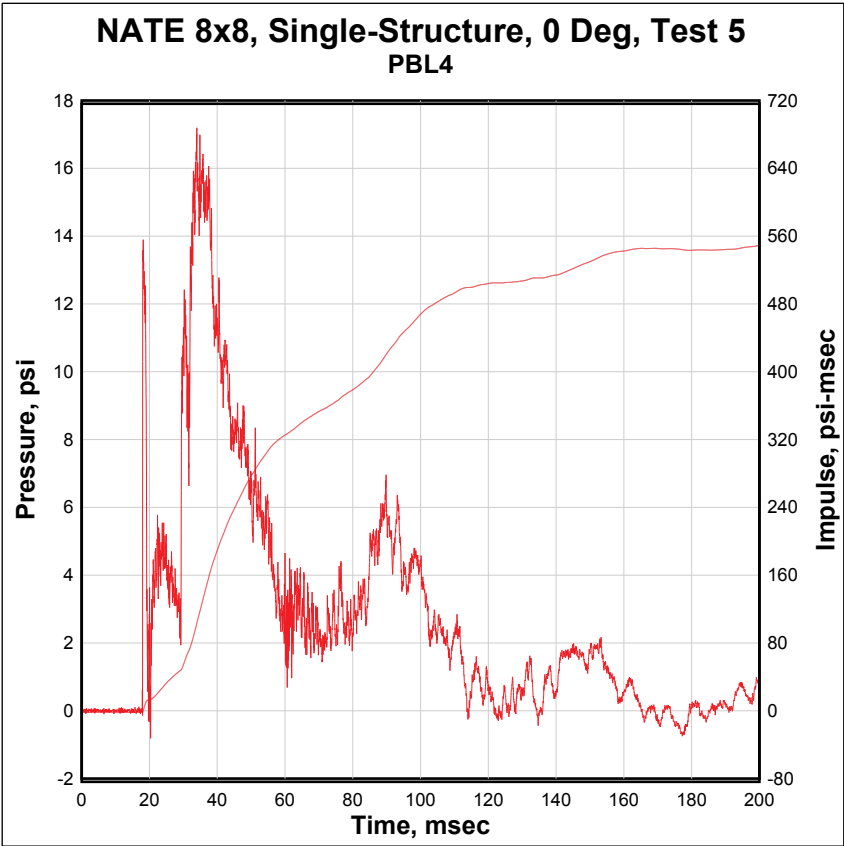


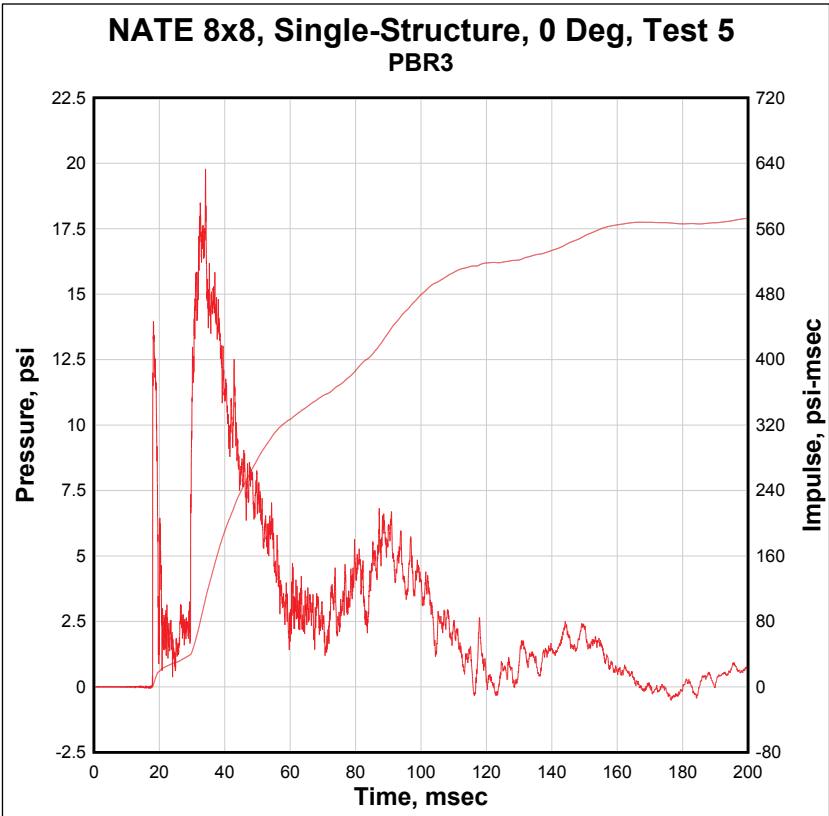
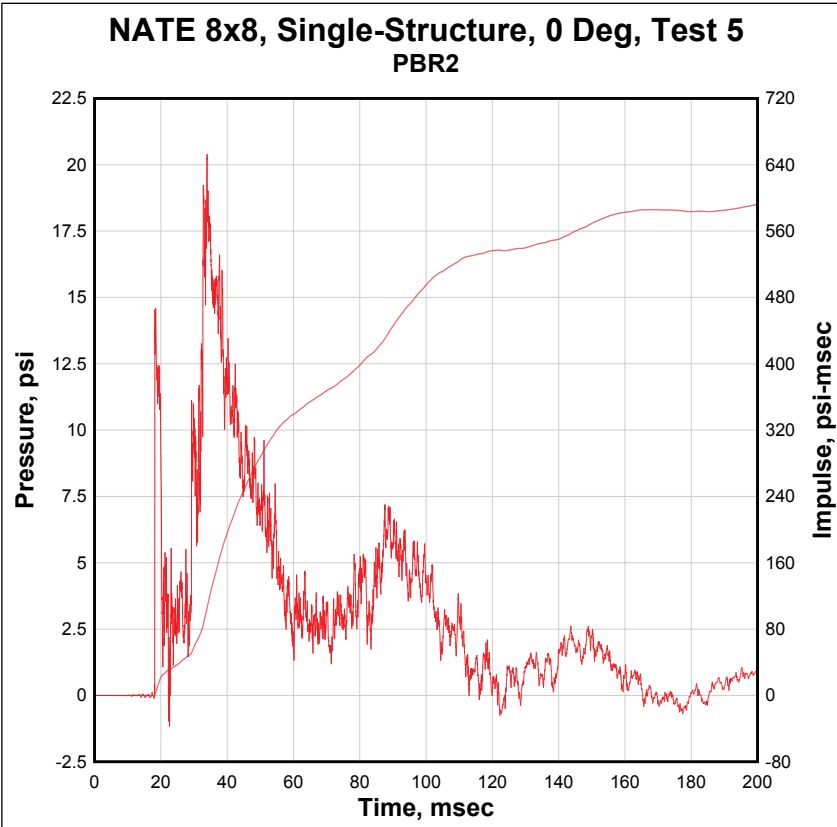


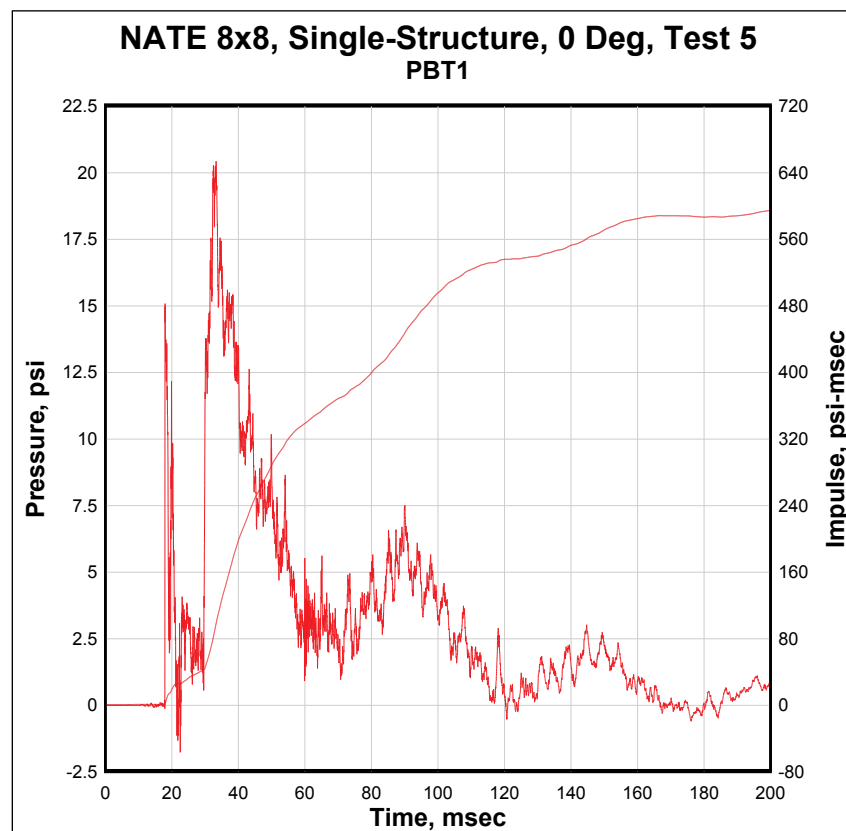
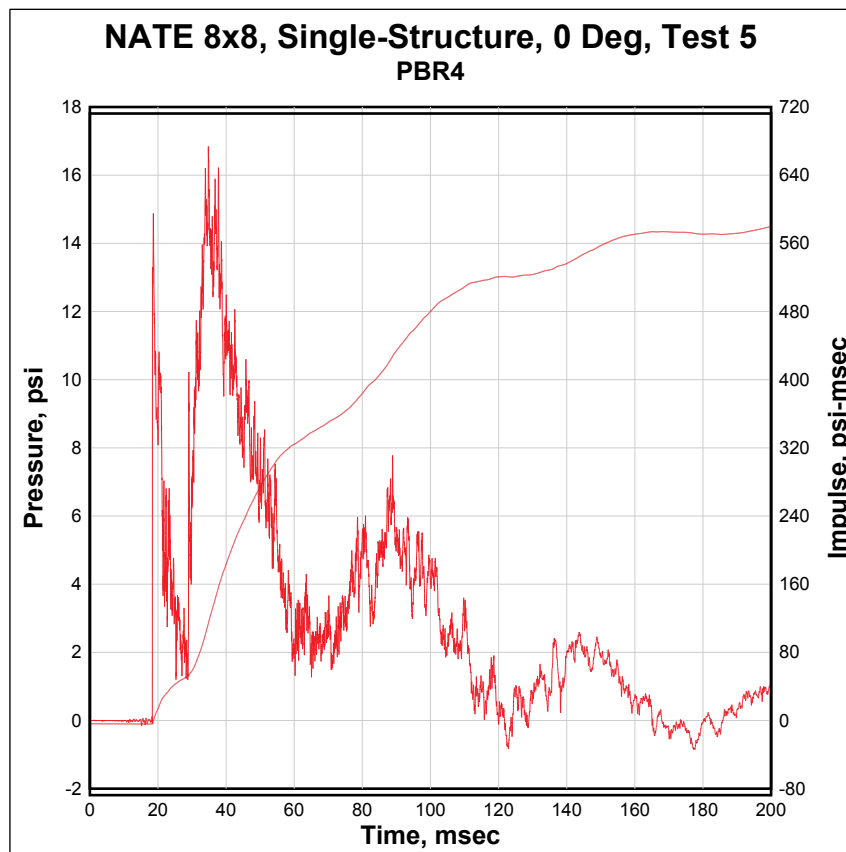


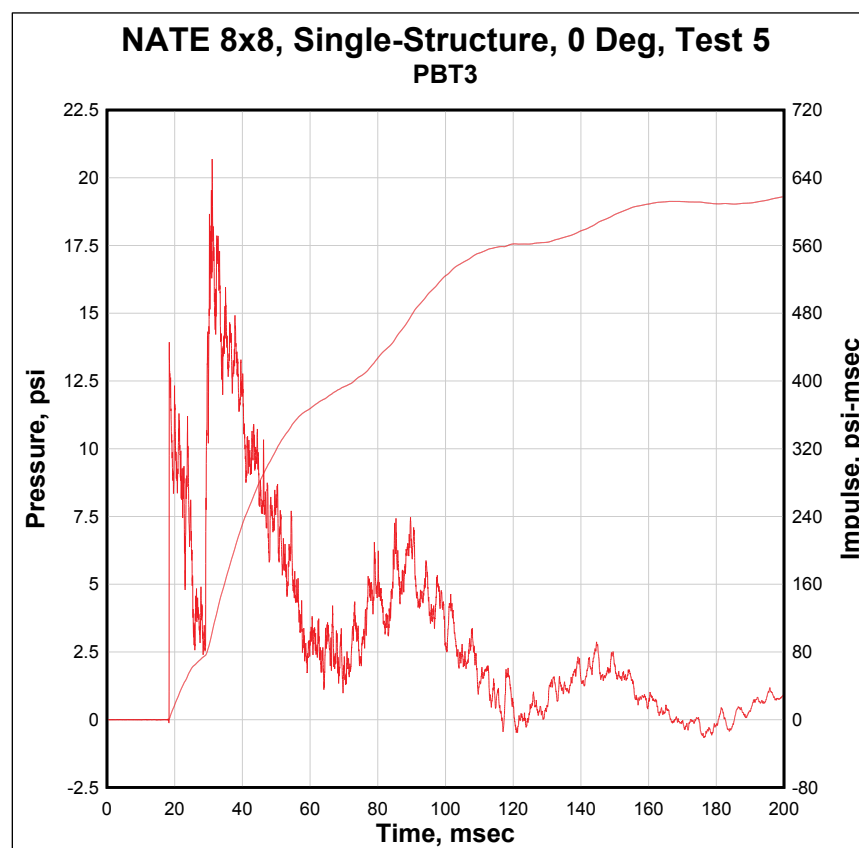
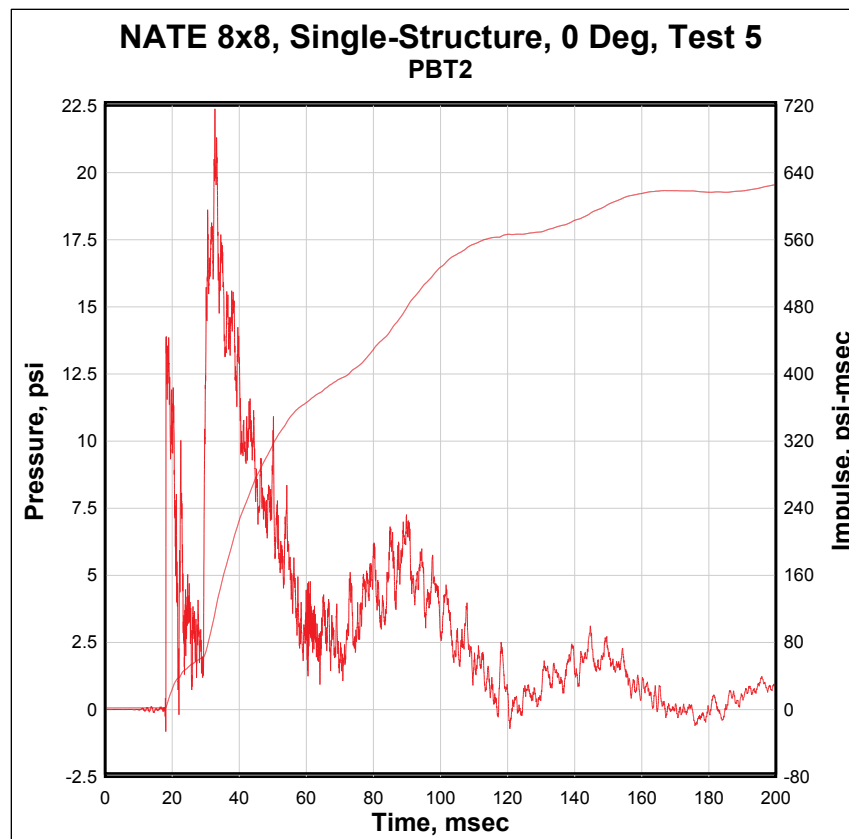


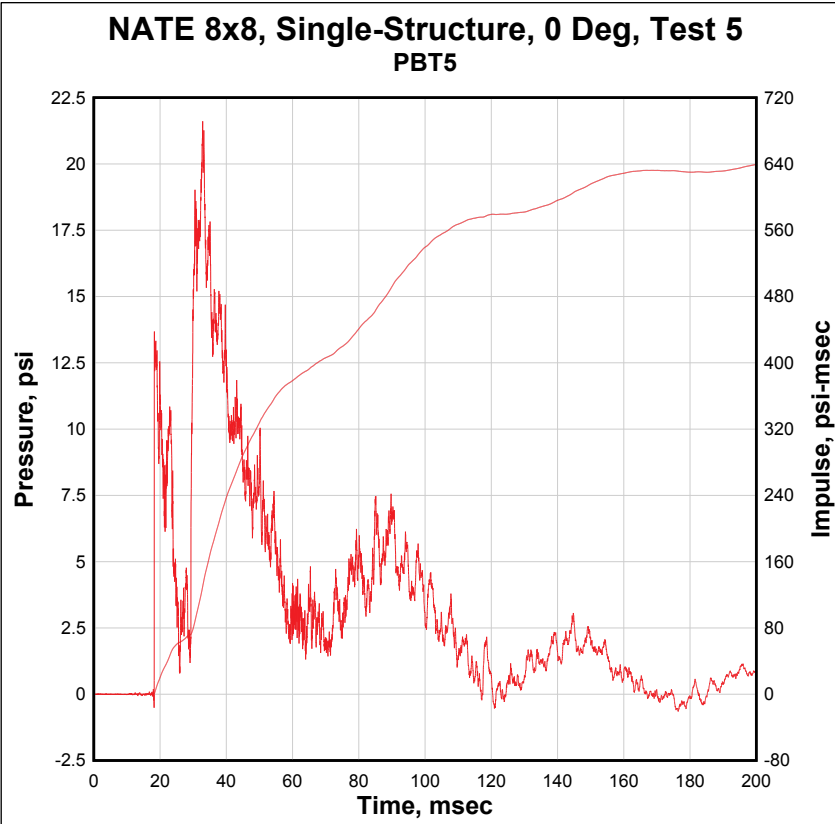
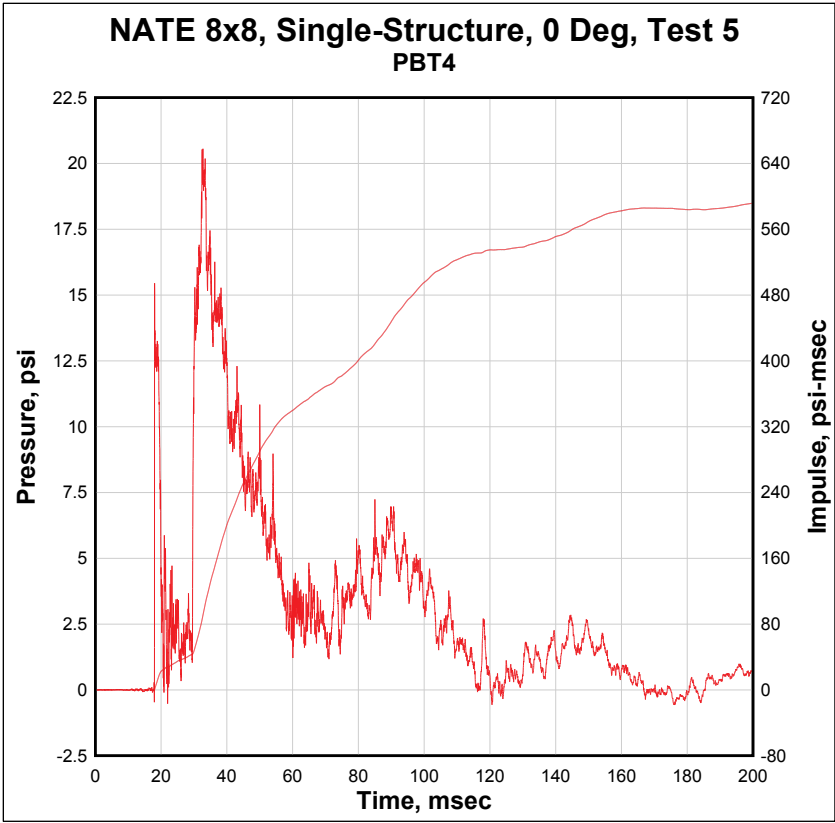


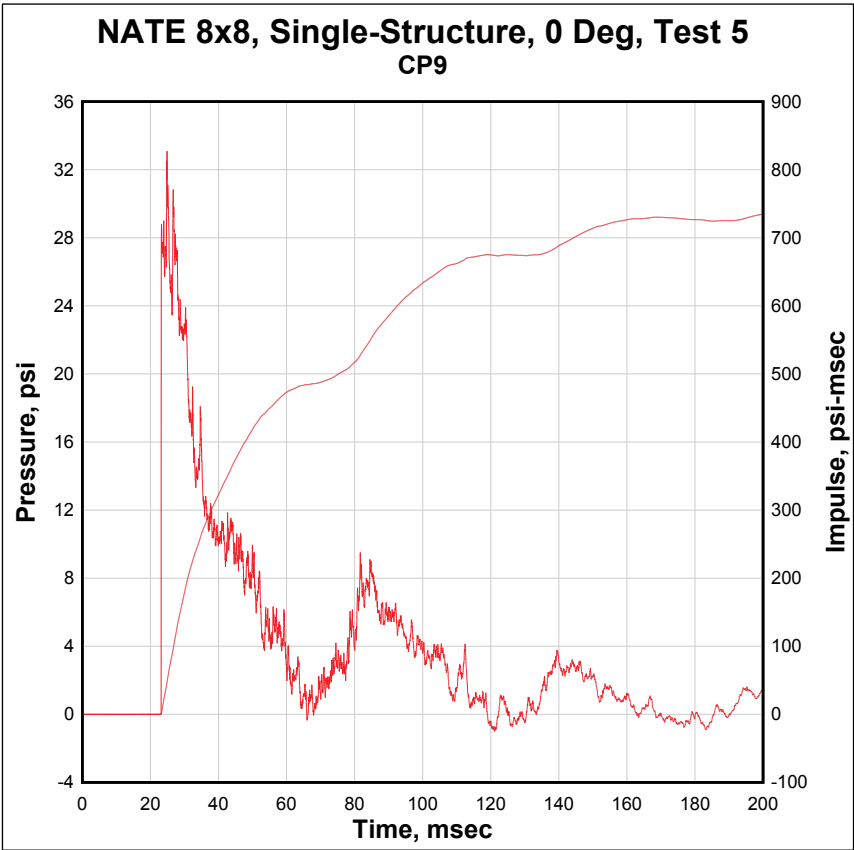
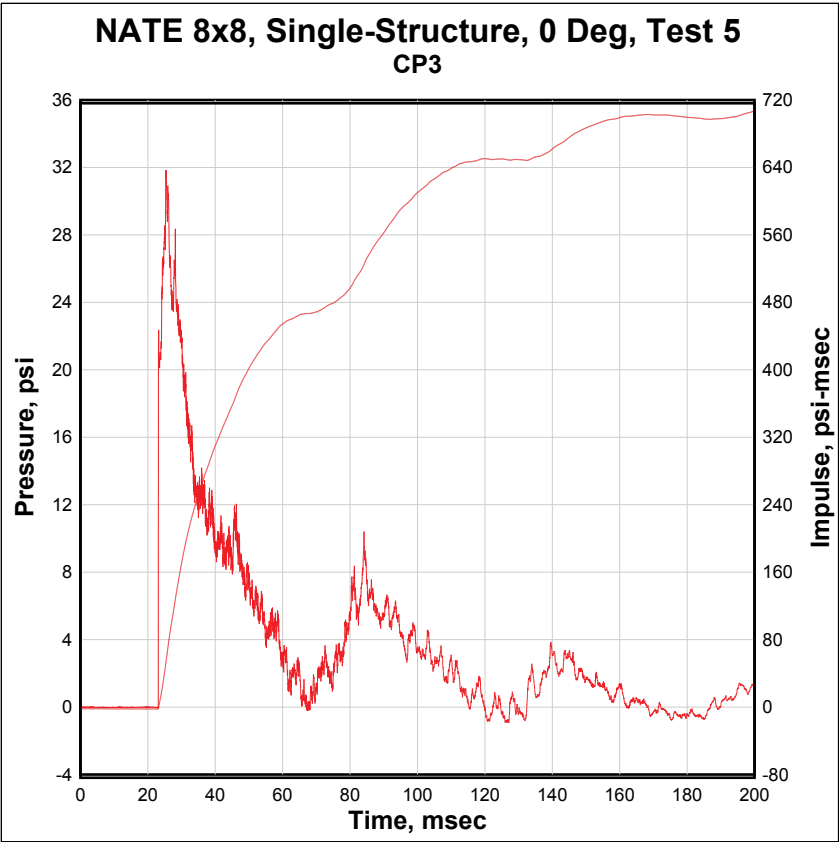












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14. ABSTRACT The Department of Defense needs the capability to accurately predict airblast environments produced by explosive detonations and their interaction with objects that create a complex geometry, such as buildings, bridges, dams, and others. First-principles computer codes are typically used to generate high-fidelity simulations of these explosive events and their effects. These codes are continuously improving, but still require validation against experimental data to establish confidence in the results produced by the simulations. This report describes a set of replicate experiments in which a small, non-responding aluminum box-type structure was installed and subjected to a simulated blast loading in a Blast Load Simulator (BLS) to provide pressure-time data at several locations on the surfaces of the structure. The BLS is a highly tunable compressed gas-driven, closed-end shock tube designed to simulate blast waveforms for explosive yields up to 20,000-lb of TNT equivalent at a peak reflected pressure up to 80 psi and a peak reflected impulse up to 1,100 psi-msec. Pressure and impulse waveforms are presented, and comparisons were made among the replicated experiments to evaluate repeatability. The uncertainty in the experimental pressures and impulses was evaluated by computing 95% confidence intervals on the results.					
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